NASA SP-530

An Exobiological Strategy for Mars Exploration

Prepared by Exobiology Program Office, NASA HQ
April 1995

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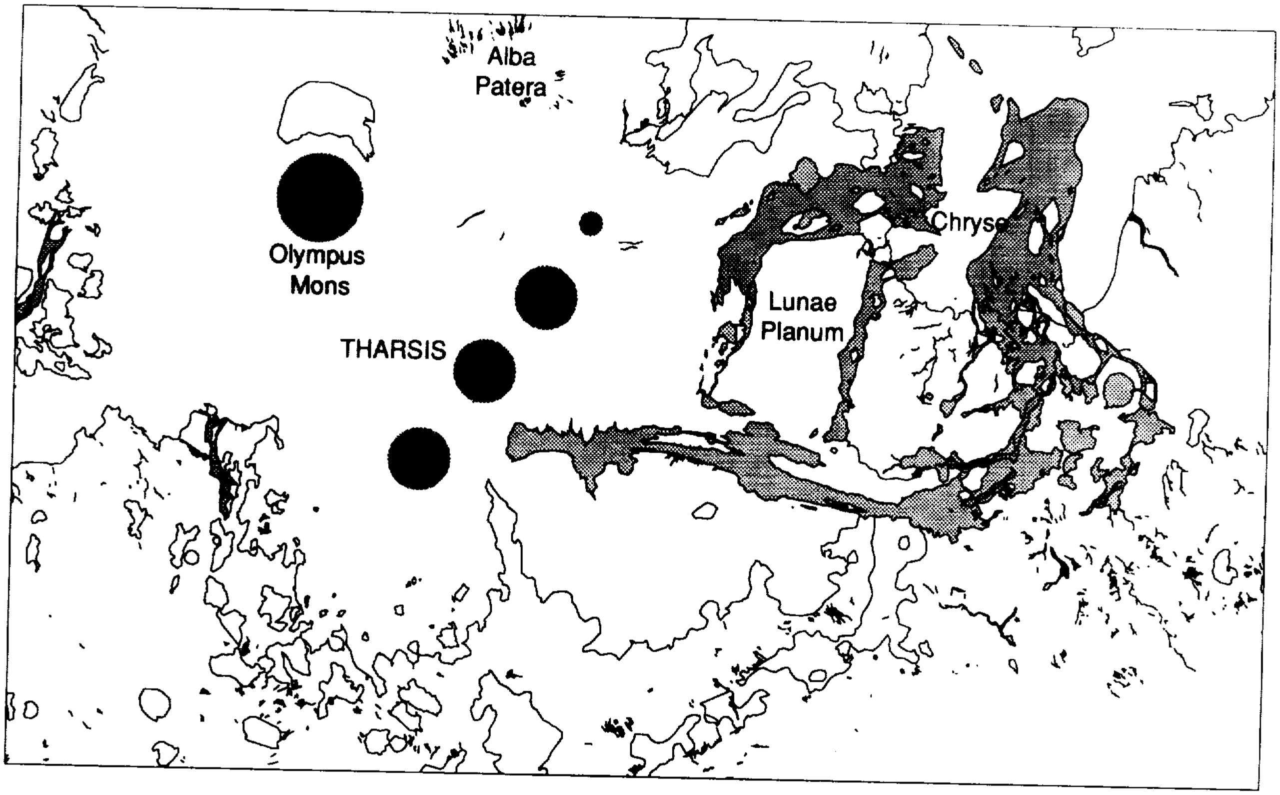
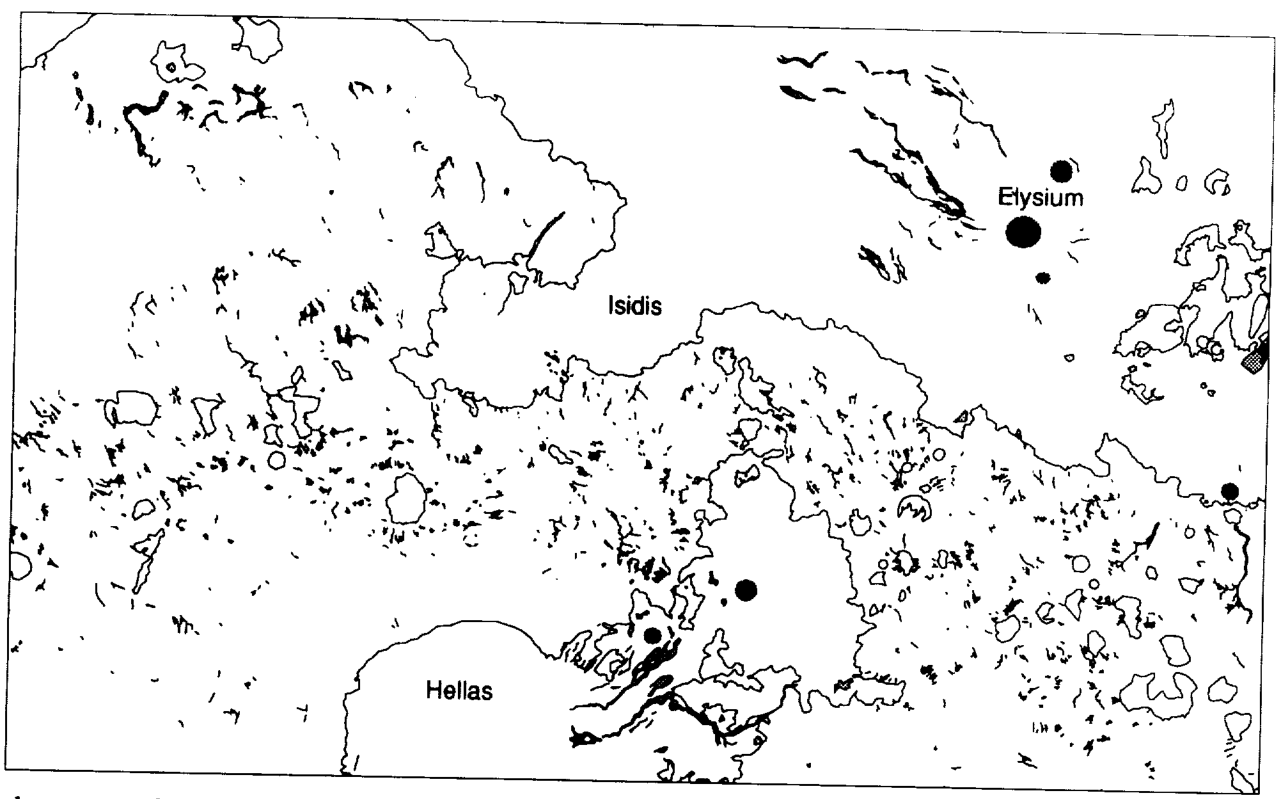




Index maps of Mars showing principal geomorphological features, from 45° S to 45° N. Upper: From 0° longitude, west to 180°; Lower: from 0°, east to 180°. Dark grey circles are volcanoes; light grey shaded areas are canyons, chaotic terrain and outflow channels. The large equatorial feature trending E-W in the upper map is Valles Marineris. The outflow region to the SE of Chryse Planitia is Ares Valles. Mars Pathfinder will land at the interface between that region and Chryse Planitia.

EXECUTIVE SUMMARY

Besides being of immense popular interest, the possibility of life on Mars, either now or in the past, is also a scientific issue of profound importance. This stems from the fact that, although theoretical considerations suggest that prebiotic chemical evolution could commonly lead to the origin of replicating life, we still know of only one planet on which life has emerged. Consequently, the conditions necessary and sufficient for life to originate are still very poorly constrained. The geologic record suggests that the environments of Mars and Earth were quite similar prior to about 3.5 billion years (Gyr) ago, when life was emerging on Earth. In particular, there is abundant evidence for liquid water, in the form of rivers, lakes and possibly even larger bodies of water, on the martian surface at that time. Because liquid water is essential for all known biology, the environment on early Mars may well have been favorable for the emergence of life. Consequently, a determination of how far Mars proceeded along the path towards life would be of fundamental significance, by greatly improving our definition of the "window of opportunity" within which life could originate. It is important to note that this remains true whether or not evidence is found for present or former life on Mars.

From these considerations, it follows that we can divide the scientific issues involved in the exobiological exploration of Mars into three general categories: (1) To what extent did prebiotic chemical evolution proceed on Mars? (2) If chemical evolution occurred, did it lead to synthesis of replicating molecules, *i.e.*, life, which subsequently became extinct? (3) If replicating systems arose on Mars, do they persist anywhere on Mars today? Although these three lines of inquiry frequently involve quite different analytical approaches, particularly in the search for extant life, the broad mission requirements of all three are quite similar, leading to a logical sequence of five explorational phases capable of accomplishing all presently defined exobiological objectives.

The first explorational phase consists of global reconnaissance. In this phase, all three elements of the strategy focus on the role of water, past or present, and on the identification of potentially fruitful sites for landed missions. Thus, global information on the distribution of water (either solid, liquid, chemically combined or physically adsorbed), global mapping of pertinent mineralogical/lithological regimes, thermal mapping, and high-resolution imaging of the martian surface are requisites for this phase of the strategy. For example, the orbital component of a search for extinct life would include the attempted detection of aqueous mineral deposits, by means of the signatures both of near-surface water, in this case chemically bound, and of characteristic mineralogies. Such sites, if found, would also be key targets for evidence of possible prebiotic chemical evolution.

Phase two of the strategy involves landed missions providing *in situ* descriptions of promising sites identified during phase 1. All aspects of the strategy converge on the need for broad-based geochemical and mineralogical characterization, culminating in elemental, molecular and isotopic analysis of the biogenic elements in a variety of microenvironments at specific sites, including analysis of volatile species. Of particular importance early in this phase is elucidating the extent to which the presence of Mars surface oxidant(s) influences the distribution of organic matter, either living or nonliving. Another key target of this phase would be assessment of the needs for future *in situ* missions which would deploy critical experiments focused on specific questions within the three categories described above.

Phase three consists of deployment of such exobiologically focused experiments. In the case of chemical evolution, the goal would be a detailed characterization of any population of organic compounds on Mars. For the issue of extinct life, the task would be a search for biomarkers and for morphological evidence of formerly living organisms. Similar approaches would be involved in the search for extant life; in the event that extant life seemed plausible, experiments to test for metabolism in living systems, similar to those of Viking, but based on a knowledge of conditions and resources at specific sites, would also be needed. Phases two and three are considered together in what follows, under the heading of "landed science".

The fourth phase, involving robotic return of martian samples to Earth, would greatly improve characterization of the organic inventory at specific martian locations, and furthermore would be essential for verification of any *in situ* evidence for extinct or extant life obtained in phase three.

Finally, the fifth phase would involve human missions and would lead to establishment of a detailed geological context for any exobiologically significant observations made previously. Also, human presence would aid in the detection of "oases" capable of promoting or supporting life that may have been missed during robotic exploration.

Although the later explorational phases tend to fall outside of the current planning horizon, missions planned for the 1996 and 1998 launch opportunities make a promising start towards implementing the earlier explorational phases outlined above. However, we have identified certain areas in which we make the following recommendations, based on the requirements of explorational exobiology:

First, we believe that it is essential that a gamma-ray/neutron spectrometer be flown on the 1998 Mars Surveyor mission, in order to provide information on the global distribution of near-surface water.

Second, we recommend development aimed at improving the spatial resolution of orbital mid-IR spectrometry to the point where it would be capable of detecting small-scale surface mineral deposits, such as those characteristic of individual hydrothermal vents or springs. Near-term deployment of such an instrument would be required because of the important role it would play in site selection for subsequent missions.

Third, we recommend immediate development of a mineral-identification capability for the earliest landed missions. This would likely take the form of a miniaturized near-to-mid-IR spectrometer plus a combined x-ray-diffraction/x-ray-fluorescence unit.

Fourth, we recommend design, construction, and near-term deployment of techniques capable of acquiring samples from locations protected from the currently harsh surface conditions on Mars. Such techniques would include a drill capable of acquiring a core several m in depth from the martian regolith, and a device capable of extracting a solid sample from beneath the surface of a martian rock..

Fifth, we recommend development of a number of analytical approaches that will be capable of detecting, and then providing detailed information about, any volatile phases, particularly organic compounds, that might be present, possibly sequestered within stable mineral phases, on or near the martian surface.

Sixth, we recommend continued support of several lines of basic R & A which provide much of the intellectual underpinning to the Mars missions.

It should be emphasized that the exobiological evolution of Mars, no matter how truncated it may have been, represents an integral part of martian history and that, as terrestrial experience has shown, such evolution is both influenced by, and in turn influences, the chemical and physical evolution of the planet. Furthermore, the observational objectives, *i.e.*, instrumentation and target selection, of exobiology overlap to a considerable extent those of geology, geochemistry and climatology on Mars. Consequently, the exploration of Mars is best viewed as a joint endeavor in which both exobiology and the disciplines of traditional planetary science work together with interests and approaches that have much in common.

The idea of searching for evidence of life on Mars may strike some as far-fetched, even fanciful. But there is a compelling logic to such a quest, as well as an equally compelling excitement. Early environments were apparently sufficiently similar on Mars and Earth, and life arose so rapidly on Earth once conditions became clement, that emergence of life on both planets at that time is scarcely less plausible than emergence on only one. Furthermore, although a fossil on Mars might seem at first like a proverbial needle in a haystack, experience on Earth tells us that *if we know where to look*, finding evidence of ancient life is not particularly difficult, especially when one considers that such evidence can be relatively widely disseminated in the form of chemical or isotopic signatures. The key is to recognize that the search for ancient life on Mars will involve a logically designed sequence of missions, each of which will focus on defining ever more closely where and how biosignatures may be found. Although one can never rule out a chance discovery, this quest should not be approached as one that will yield to a single, expeditious mission. (In fact, the proposed strategy lends itself particularly well to the use of a series of relatively small, inexpensive spacecraft, rather than a single flagship-class mission.) The search for life on Mars will take time and commitment, but the reward could be a discovery of inestimable importance, not just to science, but to humanity as a whole.

INTRODUCTION

PURPOSE OF STRATEGY DOCUMENT

Exobiological exploration encompasses many different lines of scientific inquiry, but one of the most prominent of these is the search for evidence of life elsewhere in the universe and specifically within our own solar system. It follows that there is an abiding exobiological interest in the planet Mars, which of all the planets most closely matches the conditions within which terrestrial biota are known to exist. A major goal of the highly successful Viking mission, described further below, was the search for evidence of life on the surface of Mars. Since that mission, whose results are generally interpreted as inconsistent with extant life at the two sites visited by the Viking landers, the scientific focus of planning for future Mars missions has tended towards geological, geophysical and meteorological issues, largely bypassing those of exobiology. The purpose of this document is to attempt to ensure balance in Mars mission planning by showing that (a) exobiology is an integral part of the scientific history of Mars, and (b) pursuit of exobiological goals is generally compatible with the broader-based scientific exploration of Mars.

Establishment of an exobiological strategy for Mars exploration is particularly timely in light of recent developments in several different scientific areas, such as theories of the origin and early evolution of life, Precambrian paleontology, fossilization processes, biochemistry of primitive terrestrial organisms, biology of hydrothermal systems on Earth, geomorphology of Mars, and analysis of SNC meteorites and recognition of their martian origin. These diverse lines of inquiry all combine to generate a powerful scientific justification for an exobiological exploration of Mars that goes beyond the pioneering efforts of the Viking missions.

In addition to a positive scientific context, there are good programmatic reasons for a resumption of the exobiological exploration of Mars. Those reasons may be characterized as follows.

First, the tragic loss of Mars Observer has resulted in a delay of at least four years for the global reconnaissance data needed for detailed planning of later landed missions. Following the recommendations of the Elachi Committee for recovery of Mars Observer data, those global data will now be acquired using two Mars Surveyor spacecraft scheduled for launch in 1996 and 1998, respectively.

Second, as a result of the problems plaguing the Russian economy, the Mars '94 and '96 missions have been delayed until 1996 and 1998 (or later), respectively. The Chief Scientist for these missions has indicated an interest in establishing an interdisciplinary science team which will "create recommendations...for small modification of the [spacecraft] instruments (if...possible) and recommendations for program of operation of the instruments expedient from the exobiology point of view." The earlier mission already carries a U.S. experiment designed to study the oxidant(s) believed to be responsible for elimination of organic molecules from martian soil at the two Viking landing sites.

Third, Mars Pathfinder, NASA's technical trial of a direct-landing approach, is scheduled for launch in 1996, with deployment of a mini-rover on the martian surface in 1997.

Fourth, NASA's plan to establish a geophysical/meteorological network on the martian surface, MESUR Network, has been postponed indefinitely because the estimated cost of the mission is considered prohibitive under present funding constraints. It seems likely that deployment of such a network would be feasible only within the context of a joint international project that is unlikely to occur before the 2003 launch opportunity.

Fifth, with the shelving of MESUR Network, the focus of NASA's near-term Mars strategy has shifted towards a combination of surface geology, geochemistry and climatology. Within this context, the Mars Science Working Group has recommended that the study of volatiles and climate history should constitute the near-term goal for Mars exploration.

Finally, NASA's Mission From Planet Earth Study Office (Code SX) has formally decided to make the search for life on Mars one of the overarching goals of long-term solar-system exploration.

From these considerations, it is clear that, not only is planning for Mars exploration in a very active phase at this time, but exobiology is well placed to make a major contribution to that exploration. The aim of this document is therefore to define the exobiological issues which will serve as the scientific foundation to that contribution, and to provide a scientifically sound exobiological context within which scientists, engineers and managers will be able to optimize science return from future missions. Such optimization could involve design and development of instrumentation, instrument selection or modification, definition of spacecraft operations, and/or selection of landing sites or targets for remote sensing.

OUTLINE OF APPROACH

The approach adopted in this document largely follows that employed by Klein and DeVincenzi in their report on a NASA Ames workshop on exobiological exploration of Mars held in 1992. After a brief summary of the present state of knowledge about Mars, its geology and atmosphere, and the results from the Viking biology experiments, the strategy for further exobiological exploration of Mars is discussed from the perspective of three distinct scientific aspects: The search for evidence of prebiotic chemical evolution; the search for evidence of an ancient biota that is now extinct; and the search for life extant on Mars today. Then, the extent to which missions that are currently either proposed or planned will fulfill those strategic elements is discussed. Finally, a brief discussion of planetary protection issues, more completely covered in the recent Space Studies Board report [see Additional Reading], will be followed by a set of recommendations in the areas of basic research support, development of instruments and spacecraft, and mission planning.

THE PRESENT STATE OF KNOWLEDGE

THE GEOLOGICAL HISTORY OF MARS

Mars is a geologically diverse planet with heavily cratered terrains, huge volcanoes, enormous canyons, extensive dune fields, and numerous different kinds of channels seemingly cut by running water. The geologic record preserved at the surface includes examples from the period of heavy bombardment, that ended around 3.8 Gyr ago, up to the present. Like the Earth, the surface has been affected by volcanism, tectonic activity, and the action of wind, water and ice. The geologic and climatological evolution of the two planets has, however, been very different.

The abundant evidence for liquid-water erosion on Mars is particularly intriguing since present atmospheric conditions are such that liquid water cannot exist at the surface. Surface temperatures range from 150 K at the winter pole to a daily average of 215 K at the equator. At low latitudes the diurnal temperatures range from about 170 K to 290 K. Under these conditions, and with the present low-pressure atmosphere, liquid water is unstable everywhere, and the planet has a zone compatible with buried permafrost, several hundred meters thick at the equator and kilometers thick at the poles. At low latitudes (<40^{o}), water ice will sublime into the atmosphere at rates dependent on the permeability of the overlying lithologies. Near-surface materials at low latitudes should, therefore, have lost all their unbound water. At latitudes 40-80^{o} ice is stable at depths greater than about a meter below the surface. At the poles, water ice has been detected at the north pole, where it is exposed when the overlying seasonal CO_2 cap sublimes in summer.

Highlands and plains

The surface of the planet can be divided into two main components: an ancient cratered highlands, covering most of the southern hemisphere, and low-lying plains that are mostly at high northern latitudes. Superimposed on this two-fold division are the high-standing volcanic provinces of Tharsis and Elysium. The cratered highlands cover almost two thirds of the planet. They are mostly at elevations of 1-4 km above the datum, in contrast to the northern plains which are mostly 1-2 km below the datum. The cause of the division between the highlands and plains is unclear but it may be the result of a very large impact at the end of accretion. The density of impact craters in the martian highlands is comparable to the lunar highlands. The surface clearly dates back to the very earliest history of the planet when impact rates were high. On the Moon, the transition from very high impact rates to rates comparable to the present took place around 3.8 Gyr ago, and the transition probably took place at the same time on Mars. The martian highlands differ from the lunar highlands in three main ways: most of the martian craters are highly degraded, the ejecta around craters 5-100 km in diameter is commonly arrayed in discrete lobes, each lobe being outlined by a low ridge, and in the martian highlands are numerous branching valley networks that superficially resemble terrestrial river valleys. The highly degraded nature of many of the craters has been attributed to high erosion rates on early Mars, possibly a result of warmer climatic conditions; the lobed ejecta patterns have been attributed to the pervasive presence of ground ice; and the channel networks have been attributed to fluvial activity during warmer climatic conditions.

The plains are located mostly in the northern hemisphere. The number of superimposed craters on them varies substantially, indicating that they continued to form throughout the history of the planet. The plains are diverse in origin. The most unambiguous in origin are those on which numerous flow fronts are visible. They are clearly formed from lava flows superimposed one on another, and are most common around the volcanic centers of Tharsis and Elysium. On other plains, such as Lunae Planum, flows are rare but wrinkle ridges like those on the Moon are common. These are also assumed to be volcanic. But the vast majority of the low-lying northern plains lack obvious volcanic features. Instead they are curiously textured and fractured. Many of their characteristics have been attributed to the action of ground ice, or to their location at the ends of large flood features, where lakes must have formed and sediments been deposited. In some areas, particularly around the north pole, dune fields are visible. In yet other areas are features that have been attributed to the interaction of volcanism and ground-ice. Thus, the plains appear to be complex in origin, having variously formed by volcanism and different forms of sedimentation, and then subsequently been modified by tectonism and by wind, water and ice.

Volcanism

The most prominent volcanoes are in two regions, Tharsis and Elysium. Tharsis is at the center of a bulge in the planet's surface, the deformation being over 4,000 km across and 10 km high at the center. A similar bulge centered on Elysium is around 2,000 km across and 5 km high. Three large volcanoes are close to the summit of the Tharsis bulge, and Olympus Mons, the tallest volcano on the planet, is on the northwest flank. All these volcanoes are enormous by terrestrial standards. Olympus Mons is 550 km across and 27 km high, and the three others have comparable dimensions. They all appear to have formed by a series of eruptions of fluid lava with very little pyroclastic activity. The large size of the volcanoes has been attributed to the lack of plate tectonics on Mars. The small number of superimposed impact craters on their flanks indicates that surface flows are relatively young, although the volcanoes may have been growing throughout much of Mars' history.

To the north of Tharsis is Alba Patera, the largest volcano on the planet in areal extent. It is roughly 1,500 km across but only a few km high. Flows are visible on parts of its flanks, but elsewhere the flanks of the volcano are dissected by numerous branching channels. The easily eroded, channeled deposits have been interpreted as ash. Densely dissected deposits on other volcanoes such as Ceraunius Tholus in Tharsis, Hecates Tholus in Elysium, and Tyrrhena Patera in the southern highlands have also been interpreted as formed of ash.

Thus, Mars appears to have experienced both the Hawaiian style of volcanism, involving mostly quiet effusion of fluid lava, and more violent, pyroclastic eruptions, that result in deposition of extensive ash deposits. Abundant volcanism, and evidence of water and ice suggests that hydrothermal activity has been common.

Tectonism

The most widespread indicators of surface deformation are normal faults, indicating extension, and wrinkle ridges indicating compression. The most obvious deformational features are those associated with the Tharsis bulge. Around the bulge is a vast system of radial grabens that affects about a third of the planet's surface. Circumferential wrinkle ridges are also present in places, particularly on the east side of the bulge in Lunae Planum. Both the fractures and the compressional ridges are believed to be the result of stresses in the lithosphere caused by the presence of the Tharsis bulge. Fractures also occur in other places where the crust has been differentially loaded, as around large impact basins, such as Hellas and Isidis, or around large volcanoes, such as

Elysium Mons and Pavonis Mons. There is no evidence of plate movement as on the Earth

The vast canyons on the eastern flanks of the Tharsis bulge are the most spectacular result of crustal deformation. The canyons extend from the summit of the Tharsis bulge eastward for 4,000 km until they merge with chaotic terrain and large channels south of the Chryse basin. In the central section, where several canyons merge, they form a depression 600 km across and several kilometers deep. Although the origin of the canyons is poorly understood, faulting clearly played a major role. The canyons are aligned along the Tharsis radial faults, and many of the canyon walls are straight cliffs, or have triangular faceted spurs, clearly indicating faulting. Other processes were also involved in shaping the canyons. Parts of the walls have collapsed in huge landslides, other sections of the walls are deeply gullied. Fluvial sculpture is particularly common in the eastern sections. Faulting may have created most of the initial relief, that relief then enabling other processes such as mass wasting, and fluvial action to occur. Creation of massive fault scarps may also have exposed aquifers in the canyon walls and allowed groundwater to leak into the canyons, thereby creating temporary lakes.

Water erosion

One of the most puzzling aspects of martian geology is the role that water has played in the evolution of the planet. Although liquid water is unstable at the surface under present conditions, we see abundant evidence of water erosion. The most intriguing features are large dry valleys, interpreted as having formed by large floods. Many of the valleys start in areas of what has been termed chaotic terrain in which the ground has seemingly collapsed to form a surface of jostled and tilted blocks, 1-2 km below the surrounding terrain. The largest areas of chaotic terrain are in the Margaritifer Sinus region east of the canyons and south of the Chryse basin. Large dry valleys emerge from the chaotic terrain and extend northward down the regional slope for several hundred kilometers. Several large channels to the north and east of the canyons converge on the Chryse basin and then continue further north, where they merge into the low-lying northern plains. The valleys emerge full-size and have few if any tributaries. They have streamlined walls, scoured floors, and commonly contain tear-drop-shaped islands. All these characteristics suggest that they are the result of large floods, rather than the slow erosion of running water. Although most of the floods are around the Chryse basin, they are found elsewhere. Those near Elysium and Hellas have already been mentioned. Others occur in Memnonia and western Amazonis. Impact craters superimposed on the flood channels suggest that they have a wide range of ages.

The floods were enormous, some having discharges one hundred times the annual outflow of the Mississippi river. The cause of the large floods is unclear, and they may not all be of the same origin. One possibility is that Mars has an extensive groundwater system and that in low areas the large floods are the result of extreme artesian pressures. Another possibility is catastrophic release of water dammed in lakes. Sediments within the large equatorial canyons suggest that the canyons at one time contained lakes, probably as a result of groundwater flow out from under the surrounding plateau. Catastrophic release of water from these lakes may have caused some of the large channels that connect with the canyons to the east. After the floods were over, large lakes must have been left at the ends of the channels, and several linear features at the ends of the channels have been interpreted as shorelines of former lakes.

Other fluvial features appear to be the result of slow erosion of running water. Branching valley networks are found throughout the heavily cratered terrain, and occasionally on younger surfaces. They resemble terrestrial river valleys in that they have tributaries and increase in size downstream, although only rarely can a channel be observed within the valley. The valleys are generally short compared with terrestrial river systems, most being less than a few hundred kilometers in length, so rarely does one valley system dominate drainage over a large area. The most plausible explanation for the valleys is that they formed by erosion of running water. The open nature of some networks, alcove-like terminations of tributaries, and the range of junction angles between branches are suggestive of groundwater sapping. Other networks, however, lack these characteristics, and more resemble valleys formed by surface runoff.

Ground ice

Although ice is unstable at low latitudes, it may be present at depths of a few to several hundred meters because of the slow rate of diffusion of water vapor away from the ice, through the overlying materials, into the atmosphere. The almost universal presence of lobate flows around craters larger than about 5 km suggests the presence of ground ice or groundwater everywhere at depths greater than a few hundred meters. There is evidence for near-surface ice at high latitudes. In the 35-50° latitude band in both hemispheres, debris flows commonly occur at the base of cliffs. These are convex-upward flows that extend about 20 km away from the base of the cliff. Such features are rare, if present at all, at low latitudes. The simplest explanation is that at low latitudes, when cliffs form, talus simply accumulates on the cliff slope, and so inhibits further erosion. At high latitudes, however, because of the presence of ground ice, ice could become incorporated into talus, thereby facilitating its flow away from the cliff, exposing the slope to further erosion. Debris flows are particularly common in regions of what has been termed fretted terrain, in which flat-floored valleys, filled with debris flows, extend from low-lying plains far into the cratered uplands. Formation of these valleys appears to be connected in some way with the formation of the debris flows. A general "softening" of terrain features at high latitudes has also been attributed to ground ice. At low latitudes many features, such as crater rim crests, are crisply preserved, whereas poleward of about 40° latitude similar features are rounded or muted in appearance. This softening at high latitudes is generally attributed to ice-abetted creep of the local lithic materials.

Poles

At each pole, and extending outward to about the 80° latitude circle, is a stack of layered sediments. They are at least 4-6 km thick in the north and at least 1-2 km thick in the south. Incised into the smooth upper surface of the deposits are numerous valleys and low escarpments. These curl out from the pole in a counterclockwise direction in the north and a predominantly clockwise direction in the south. Between the valleys, which are roughly equally spaced and 50 km apart, the surface of the deposits is very smooth and almost crater-free. For most of the year the layered deposits are covered with CO_2 frost, but in summer they become partly defrosted. The layering is best seen as a fine horizontal banding on defrosted slopes. The deposits are believed to be composed of dust and ice, with the layering caused by different proportions of the two components. The scarcity of impact craters indicates relatively recent activity, although the age of the deposits could still be on the order of hundreds of Myr.

The layering suggests cyclic sedimentation, and the origin of the deposits may be connected in some way with the obliquity cycle. The obliquity is the angle between the equatorial plane of a planet and the orbital plane, and in the case of Mars is thought to oscillate chaotically over a wide range of values. At the highest obliquity twice as much insolation falls on the poles as at the lowest obliquity. As a consequence, the capacity of the high latitude regolith to hold adsorbed CO_2, the size of the CO_2 cap, and the atmospheric pressure are expected to change with the obliquity cycle. These changes could affect global wind regimes, dust-storm activity and sedimentation rates at the poles, thereby causing episodic sedimentation. Layering would also be caused by any event that resulted in large amounts of water vapor being introduced into the atmosphere. Possibilities are volcanic eruptions, large floods, and cometary impacts. These would all result in deposition of an ice-rich layer at the poles.

Conclusions

Mars, like the Earth, has had a diverse geologic history. An ancient heavily cratered surface preserves evidence of events of the planet's earliest history. Volcanic activity continued throughout the planet's history, possibly to the present, and resulted in the formation of extensive lava plains and large shield volcanoes. Much of the volcanic activity has been in two provinces, Tharsis and Elysium, which are at the centers of large bulges in the planet's surface. The Tharsis bulge caused fracturing over about one third of the planet's surface, and this fracturing may underlie the formation of enormous canyons down the east flank of the bulge. Massive floods of water have periodically flowed across the surface, some being triggered in some way by volcanism. In addition, dissection of some surfaces, particularly in the ancient cratered highlands, by small branching valley networks indicates slow erosion by liquid water and possibly massive global climate changes. The morphology of impact craters, and presence of numerous features suggestive of ground ice, indicate that ice is abundant at shallow depths at high latitudes, and at greater depths at low latitudes. Thus Mars is a planet on which most of the

Dao Vallis is a large outflow channel on the southern flank of the ancient martian volcano, Hadriaca Patera, that appears to have formed by the interaction of subsurface heat and ground ice. The floor and head wall of the channel could have sustained hydrothermal systems for a long period, depositing thermal-spring sinters of high priority for exopaleontology.

geologic processes familiar to us here on Earth have operated. The two planets are, however, also very different. The lack of plate tectonics on Mars has led to greater stability of the surface and to accumulated development of enormous volcanoes and canyons. In addition, the ineffectiveness of water erosion in eliminating relief has led to almost perfect preservation of features widely ranging in age. Despite the excellent photographic coverage and near-perfect preservation, the origin of many of the features remains obscure.

EVOLUTION OF THE MARTIAN ATMOSPHERE

Mars shows clear geological evidence for liquid water having existed on the surface, yet present-day conditions are such that liquid water could exist only under transient, metastable conditions. The martian atmosphere and volatile systems are key components to issues such as the possible origin of life at some time during Mars' history and the evolution of the martian climate. Our understanding of climate change is clearly driven by the geological evidence, as discussed in the previous section. Degradation rates were much higher prior to about 3.5 Gyr ago, and degradation styles are suggestive of the presence of liquid water on the surface as an erosive agent. In addition, the valley networks on the ancient terrain have been interpreted as being indicative of liquid water flowing either on or beneath the surface; the features were eroded either by runoff of precipitation or by sapping. All of the evidence suggests that the climate during the earliest epochs was fundamentally different from that at the present, although quantifying this difference is not easy.

In addition, enrichment in the ratio of $^{15}N/^{14}N$ in atmospheric nitrogen is usually interpreted as being due to the preferential loss of the lighter isotope to space via nonthermal escape. As much as 99% of the original nitrogen inventory could have been lost. Similarly, enrichment in the ratio of D/H in atmospheric water also is interpreted as being indicative of loss to space. The D/H ratio is enriched by about five times, compared to its initial value (based on terrestrial and meteoritic values); preferential loss to space of the lighter isotope is the only mechanism which can produce this large a fractionation. Up to ~99% of the water must have been lost to space. Spacecraft measurements demonstrate that loss of hydrogen and oxygen occurs at the present.

There are three common approaches to understanding the history of the martian atmosphere and of water in particular:

First, from the geological perspective, the issues around the early atmosphere involve (i) understanding what climatic conditions were required to produce the early extensive erosion of Mars' surface and to allow the valley networks to form, and then (ii) what atmospheric composition can produce such conditions.

The degradation of craters on the older surfaces is the most compelling evidence for climate change. Craters smaller than about 15 km diameter have been removed almost completely, and the remaining craters have been eroded substantially. Erosion by a surficial process is the best explanation for these features. The cratering age determinations indicate that the erosion ceased at about 3.5 Gyr ago.

The valley networks appear to be dendritic drainage patterns, and occur predominantly on the older surfaces. The mechanism of formation could be either runoff of precipitation or sapping by subsurface water, and each mechanism is favored by some surface features.

That these climate-related features appear only on the older surfaces indicates that they cannot form under the present climatic conditions. However, the ambient conditions during those epochs are still extremely uncertain. Exactly what surface temperature is required will depend on what the mechanism(s) are for formation of the geologic features. Compared to the average surface temperature today, about 220 K, temperatures of 245 K are often cited as the minimum average required for occasional liquid water, and 273 K, of course, for ubiquitous liquid water.

The simplest way to raise the average temperature is with an atmospheric greenhouse, such as by CO_2 in the atmosphere. However, a thick CO_2 atmosphere during early epochs would saturate and condense at high altitudes, thereby limiting the amount of CO_2 that could reside in the atmosphere. The 1 to 2 bars CO_2 that can reside in the atmosphere during those epochs is insufficient to raise the temperatures adequately. Additional heating could come from other greenhouse gases, such as methane or ammonia, but their presence and stability is uncertain.

Geological estimates of the total inventory of water are based on the amounts of water released from volcanic activity (both extrusive and intrusive) and from catastrophic flooding. The crust is estimated to hold perhaps the equivalent of a layer of water 0.5 km thick, and 10 to 20% of this is estimated to have been released to the surface.

Second, from the geochemical per-spective, estimates of the volatile inventory of the whole planet come from our understanding of the volatile abundances in the material from which Mars accreted and from the geochemistry of the materials sampled in the martian regolith and in the SNC meteorites. As such, they are very uncertain. Estimates can be made of the amount of water, for example, incorporated into the accreting Mars, based on the water content of the materials from which it accreted. These estimates vary, up to the equivalent of a couple hundred meters of water, assuming that all of the water outgassed to the surface. Clearly, this is insufficient to account for the crustal water as inferred from the geology. One solution to this problem allows for a late-accreting veneer of volatile-rich materials (such as comets) to supply the martian volatiles. Of course, in this case, the total size of this veneer is uncertain, and there can be no first-principles estimate of the initial water content of Mars.

Estimates of the escape rates of atmospheric species are also uncertain when integrated over geologic time, but they can be constrained by present-day ratios of isotopes of stable elements in the atmosphere. Loss to space can occur by Jeans' escape for hydrogen and by various nonthermal escape processes for heavier elements. Nonthermal escape includes photochemical processes such as dissociative recombination (of nitrogen, for example), or sputtering ejection by solar-wind pick-up ions. The latter process can be responsible for loss of a substantial fraction of a bar of CO_2; it can also be responsible for loss of the light noble gases such as argon or neon.

Interpretation of isotopic ratios is confusing for hydrogen, oxygen, and carbon, because the atmospheric species can exchange with non-atmospheric reservoirs (such as the polar caps or the deep crust) of uncertain size. The noble-gas isotopic ratios are much easier to interpret, however, because the nonexchangeable noble-gas reservoir is quite small, relative to the atmospheric reservoir. For example, the observed ratio of $^{38}Ar/^{36}Ar$ implies loss of between 50 and >90 % of the atmospheric argon. Therefore, the nonradiogenic argon abundance in the present atmosphere cannot be used as an indicator of volatile inventory or outgassing efficiency without augmenting it to account for sputtering loss. Sputtering loss also must be accounted for in assessing the inventory of climatic volatiles such as water and carbon dioxide. A synthesis of the data suggests that substantial volatiles have been lost to space, with most of the loss occurring at about the same time that the geology suggests that the climate was changing.

Of additional relevance, the abundances of helium and neon in the atmosphere and the ratio of $^{22}Ne/^{20}Ne$, in the presence of rapid loss by sputtering, require that juvenile volatiles continue to be outgassed to the atmosphere during recent epochs.

The geochemical and geological inferences overlap in one important area for understanding the evolution of martian volatiles, namely hydrothermal systems. Volcanism and impacts provide abundant sources of heat, and there is considerable evidence for the presence of water, as discussed above. The effects of hydrothermal alteration are seen in SNC meteorites, and there is some evidence that hydrothermal systems may have played a role in the formation of the valley networks and other surface features. In terms of atmospheric evolution, however, the key issue is the recent realization that water in such systems exchanges between the crust and the atmosphere. This evidence lies in the D/H ratios measured in water-bearing minerals in some SNC meteorites, which can have values as high as the martian atmospheric value (five times the terrestrial ratio). As such a large enrichment can only occur by escape to space, the high crustal values require exchange between the atmosphere and crust. This exchange has important implications for the abundance and history of water, and possibly for other volatiles as well.

Finally, there are possible variations in the atmosphere on shorter timescales. Geological evidence for changes in the atmosphere come from the polar caps and from putative shoreline features seen in various locations. Layers within the polar caps appear to consist of alternating laminae of water-ice-rich and dust-rich materials. The layers are presumed to result from quasi-periodic variations in the martian climate. The large swings in the axial obliquity, which occur on timescales of about 10^5 to

10^6 years and longer, are thought to be responsible for the climate variations. The long-term average obliquity wanders chaotically with a timescale of about 10^7 years, and values as large as 60^o may have occurred in the recent geological past. The polar deposits contain a significant amount of CO_2 and/or H_2O, and these may be released into the atmosphere at high obliquity.

Geologically, observations of benches seen in certain locations in the northern lowlands have been interpreted as having been carved by wave action from a putative northern ocean. Ages of these features would require the ocean to have been there during parts of the last 3.5 Gyr. Although the outflow channels certainly debouched into the lowlands and may have created standing bodies of water throughout this period, it is not clear that these could have remained liquid long enough for waves to have cut such features. The possible release of CO_2 and water from the polar caps during periods of high obliquity, on the other hand, may have provided a mechanism for stabilizing water temporarily.

In summary, all of the available evidence related to the evolution of the atmosphere and volatile system suggests the following:

(i) The climate on Mars was substantially different during the earliest epochs, prior to about 3.5 Gyr ago.

(ii) Although there is still debate on this topic, it appears likely that the early atmosphere was warmer than the present one and may have allowed at least occasional occurrences of precipitation and surface runoff.

(iii) The change in climate around 3.5 Gyr ago may have been caused at least in part by loss of volatiles to space by nonthermal escape and by the sequestration of volatiles into the polar caps.

(iv) The present-day climate contains a thin, dry atmosphere, in which water can be present as a liquid only under special conditions and then only as an unstable, transient phase.

(v) There is evidence for active and abundant hydrothermal systems, existing throughout much of martian history, that contain substantial amounts of water that may exchange with the atmosphere.

(vi) Although very speculative, it is possible that there may have been periods in the last few Gyr during which volatiles were released into the atmosphere, possibly from the polar caps during periods of high obliquity, resulting in occasional episodes of more-clement climate.

RESULTS OF VIKING BIOLOGY EXPERIMENTS

Background

From a biological point of view, the Viking mission to Mars in the late 1970's can be interpreted as a test of the Oparin-Haldane hypothesis of chemical evolution. Taking into account that the early histories of Mars and Earth were probably similar, and that terrestrial life appears to have originated on Earth very early - from materials that could well have been present also on Mars - it is not unreasonable to assume that chemical evolution, leading to complex organic compounds capable of replication, could have also occurred on Mars. Further, if replicating systems did appear on Mars in an earlier, more benign, environment than exists today, the question is whether these ancient organisms were able to adapt to worsening conditions on that planet, as it lost its surface water and much of its atmosphere, and cooled to its present cold, arid, seemingly hostile condition. The biological experiments aboard the Viking spacecraft were intended to probe this possibility.

During the 1960's numerous approaches were proposed for the detection of a martian biota ranging from physical to chemical and biological measurements of martian surface samples. For the Viking mission, the general approach selected was to test samples for possible metabolic activity of indigenous organisms, predicated on the assumption that using such an approach would allow the amplification of possibly weak biological signals by prolonged incubations.

Relevant nonbiological Viking instruments

In addition to the Viking Biology Instruments discussed below, it is important to emphasize that several other instruments aboard the Viking landers ultimately made substantial contributions to our understanding of the status of extant biology on that planet. These included an extremely sensitive gas chromatograph-mass spectrometer for elucidating the nature of organic compounds that might be present in martian surface material, and also for determining the composition of the martian atmosphere; an X-ray fluorescence instrument for analyzing the elemental composition of surface samples; and an imaging system capable of surveying the local surroundings in black and white and color, over the course of the seasons.

Major findings of interest in connection with the subject at hand were: a) that no organic compounds were detected in surface samples; b) that the inorganic elemental composition of surface samples were consistent with a mixture of iron-rich (smectite) clays, magnesium sulfate, and iron oxides; c) that, in addition to carbon dioxide and carbon monoxide, the surface atmosphere contained about 2.5% nitrogen and 0.15% oxygen; and d) that no structures uniquely attributable to biological entities were present in more than 4500 images obtained from the two landers.

The Viking biology experiments

For the metabolic experiments conducted on the two Viking landers, three different instruments were included, based on four different assumptions about the nature of martian biota. Using these instruments, a variety of environmental conditions could be provided for incubating samples. In addition, in each case, provision was also made to heat surface samples to temperatures of 140 to 180°C prior to incubation to serve as controls for provisionally positive results. In all, a total of 26 separate incubations were made at the two lander sites.

The Pyrolytic Release Experiment

This experiment, which was performed 9 times, had as its underlying basis the assumption that some photosynthetic species, capable of assimilating either CO_2 or CO, might be present in the martian surface. Accordingly, samples were first incubated with ^{14}C-labeled CO_2 and CO in the presence of a xenon arc lamp to simulate solar illumination. After several days, the samples were subjected to high temperatures to drive off and trap any organics on a column and, during this process, to free any trapped organics from initial radioactive gases. After this, the organics were released from the column by heating to pyrolyzing temperatures, the resulting pyrolysis products being monitored by a ^{14}C detector. Later modifications of this basic protocol included incubations in the dark and with the addition of traces of water vapor during incubation.

Extremely small, but statistically significant, amounts of incorporation of the initial gas mixture (presumably into organic compounds) were seen in these experiments. However, the results have been interpreted as being nonbiological on the following grounds: heating one sample to "sterilizing" temperature (90°C) for 2 hr did not reduce the level of incorporation; addition of water vapor (to supply reducing power for the reaction) totally abolished the reaction; and the reaction proceeded in the dark. To date, no satisfactory explanation has been given to account for these results.

The Labeled Release Experiment

This experiment was based on the assumption that organisms might be present in the surface of Mars that were capable of metabolizing simple carbon compounds similar to those readily formed in laboratory simulations of early organic chemical evolution. For this experiment, which was carried out 10 times, a dilute aqueous solution of 1, 2, and 3-carbon compounds, labeled with ^{14}C in all carbon atoms, was injected onto samples and the system was incubated for periods of up to several months. During incubation, the head-space was monitored by a ^{14}C detector for evidence of degradation of the substrate molecules.

The major findings from this experiment were that each time a fresh surface sample was incubated, there was a rapid evolution of radioactive gas, amounting to about 10-15% of the initial radioactivity supplied and that samples heated to 160°C were completely inhibited, and samples heated to 50°C partially inhibited, in the evolution of radioactive gas. These results are consistent with pre-Viking criteria of a positive response. Nevertheless, there are several considerations that argue against assigning such a conclusion to these experiments, the most significant of which are the data from the GC-MS and Gas Exchange experiments which point to highly reactive substances in the martian surface that could readily oxidize the low-molecular-weight substrates used in this experiment. To resolve this issue, further experiments with martian material and with simulated martian environments are clearly indicated.

The Gas Exchange Experiment ("wet" mode)

Here the assumption was made that surface samples contained heterotrophic micro-organisms requiring organic substrates and possibly various organic growth factors for their metabolism, and that metabolism would involve the uptake or release of metabolic gases. To elicit the growth of such organisms, a complex aqueous solution, containing 19 amino acids and over a dozen growth factors, plus numerous inorganic salts, was added to surface samples. Metabolism was monitored with a gas chromatograph capable of measuring changes for a number of metabolically prominent gases, such as H_2, N_2, O_2, CO_2, and CH_4. Three experiments were conducted in this mode, with incubation times of up to several months. The data gave no indication of metabolic activity; the main gas change observed under these conditions was a slow, steady release of CO_2 over the course of incubation, which has been interpreted as resulting from a slow oxidation of one or more of the organic constituents.

The Gas Exchange Experiment ("humid" mode)

This mode of conducting the gas exchange experiment was based on an assumption that indigenous organisms only required the presence of moisture in order to elicit their metabolism. Accordingly, for these incubations, after surface samples were dispensed into a porous cup in the incubation chamber, nutrient solution (described above) was allowed to enter the incubation chamber without touching the samples, and the chamber was sealed. Under these conditions, the samples became humidified without coming into contact with added nutrients. In each of the three experiments carried out under these conditions, there was an unanticipated, rapid, evolution of O_2 into the headspace. That this reaction was nonbiological is very likely for a number of reasons: The reaction was extremely rapid; release of O_2 took place in the dark; and, finally, after prior heating of the samples at 145^{o}C for 3.5 hr the reaction still took place. While many explanations have been offered for the reactivity seen in these experiments, the prevalence of one or more reactive oxidants in the surface material seems to hold the most credence at present. However, the actual mechanism underlying this reactivity remains to be ascertained in future experimentation with martian samples. Of interest is the observation that the data from the three samples tested in this manner suggest an inverse relationship between the active agent in the surface and the prior water exposure of the samples.

Summary

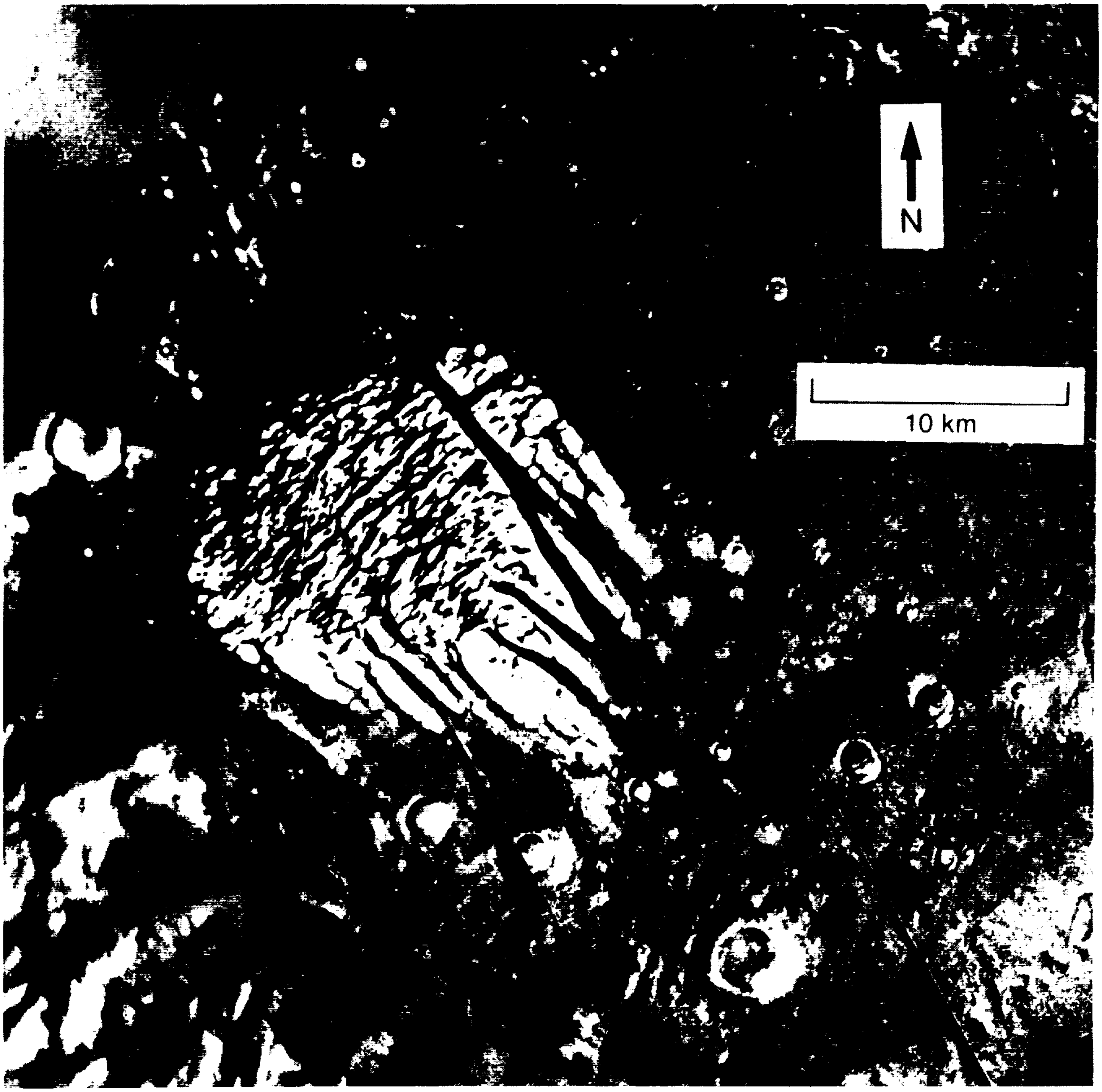
Taking into account all of the data summarized above, it is fair to state that the Viking experiments ruled out a number of possible scenarios for biology on the surface of Mars, but left open the possibility that organisms might still exist in some cryptic environment - yet to be discovered. Viking also raised a number of important questions: Are organic compounds accessible anywhere on the planet? What is the nature of the reactive oxidant in surface material, and how is it distributed on the planet? Are there regions on or near the surface of Mars that sustain indigenous organisms?

SEARCH FOR EVIDENCE OF PREBIOTIC CHEMISTRY

INTRODUCTION

It is possible that *all* martian chemistry is prebiotic, in the sense that it took place without the agency of a pre-existing biota. Whether it is prebiotic in the sense of having led to a martian biota is less clear. In either case, however, determination of the extent to which such organic chemical evolution proceeded on Mars is of fundamental importance to the study of life's origins. The focus here is on processes leading to the formation of substances that might ultimately have combined to yield self-replicating, self-sustaining organisms. Such reactions must have run their course *somewhere, sometime*, at least once; presumably on the early Earth before 3.5 Gyr ago. Because Earth's primitive biota would have quickly eliminated the organic chemistry from which it sprang, to say nothing of the degradative effects of tectonic activity, no extant terrestrial records allow reconstruction of that chemical pathway. The most likely site where such a record may have been preserved is the planet Mars.

It follows that, although popular interest is generally associated with the possibility of life, either extinct or extant, on Mars, we will consider here an alternative that is of comparable scientific importance: that the prebiotic chemical processes which led eventually to life on Earth got started on Mars but never ran to completion. A very wide range of possibilities is open. A few or many organic compounds might have formed before conditions



"White Rock" is a wind-eroded bedrock form of anomalously bright albedo that is situated within an 80 km diameter crater in the Sinus Sabaeus region of Mars. "White Rock" has been interpreted to be an evaporite deposit of chemically precipitated minerals that could have entrapped and preserved fossil organisms. The thickness of the deposit suggests that the hydrologic system responsible for the deposit operated here for a long period of time.

became unfavorable. But the idea is attractive because conditions early in martian history appear to have been at least somewhat similar to those on Earth. Chemical processes on Mars might then have resembled those preceding the development of life on Earth. Subsequently, however, the surface histories of these planets have differed significantly. While the Earth's earliest sediments have been destroyed or heavily altered, much of the martian surface appears to have been relatively undisturbed, perhaps since about 3.5 Gyr ago. To whatever extent minerals and other compounds have been preserved, examination of them can provide at least a view of conditions prevailing on Mars and, possibly, unique information about prebiotic processes in the solar system. This would be of unparalleled value and interest.

Two mistakes can be imagined: first, focusing inappropriately and prematurely on prebiotic chemical issues; second, ignoring them. Before investigations of martian prebiotic chemistry can be intelligently designed or any conceivable results placed in context, much must be learned about the general chemistry of Mars. But as more general measurements are defined, it would be well to consider features that would provide information bearing particularly on prebiotic chemistry. The evolution of the volatile inventory and the chemistry of carbon, hydrogen, nitrogen, oxygen, sulfur, and phosphorus are of particular interest. These elements form the reactants in prebiotic chemical reactions. Most are also the volatile elements which exchange between the atmosphere and crust of the planet, and are therefore central to unveiling the geologic history of Mars, the present-day climate, and other planetary-science objectives.

The detailed exploration of Mars by orbiting satellites and landers comes at a time when many new ideas concerning prebiotic chemistry and conditions on the early Earth require innovative, field-based tests. A decade and a half ago, the study of prebiotic chemistry was dominated by a single paradigm consisting of the following sequential steps: (1) synthesis of organic compounds from reduced gases in the atmosphere and transfer of these compounds to the ocean producing (2) a 'prebiotic soup' of a concentration high enough to lead to (3) chemical evolution of biopolymers corresponding to early versions of DNA and proteins which organize themselves into (4) a heterotrophic organism which could obtain energy from compounds in the soup and lead eventually through Darwinian evolution to (5) autotrophs capable of feeding themselves through photosynthesis. Research in recent years has challenged all aspects of this paradigm as well as the assumptions on which it is based.

Atmospheric scientists have challenged the survivability of reduced gases in the presence of water vapor in the early atmosphere. Water photodissociates, yielding hydroxyl radicals which rapidly oxidize reduced gases. On the early Earth, for example, ammonia and methane would have been converted to nitrogen and carbon dioxide. Providing an alternative, geochemists have identified sources of organic synthesis through CO_2 reduction, based on the recognition of naturally occurring metastable equilibrium states which are reached between CO_2 and organic compounds in sedimentary basins and hydrothermal systems. In addition, considerable attention has focused on reactions involving iron sulfides, iron oxides, gases and aqueous solutions as potential sources of energy for early metabolic systems. New theories are emerging, diverse viewpoints are finding encouragement, and there are several competing hypotheses regarding prebiotic chemical systems. New data, new observations, and new techniques are required. Although much can and will be done in the lab, the examination of natural systems is essential and Mars provides an ideal site.

THE GEOCHEMICAL CONTEXT FOR PREBIOTIC CHEMISTRY

The cycling of volatile elements through the crust and the atmosphere of Mars has enormous implications for prebiotic chemistry. Three things are essential in order for a chemical source of energy to exist and be usable by a metabolic system. There must be chemical reactions which are (1) thermodynamically favored but (2) kinetically inhibited, and (3) the reactants must be supplied continuously by normal geochemical processes. Natural disequilibrium states meeting this description are numerous and span the range from weathering of basalt to stress-generating phase transitions in the Earth's mantle. Among the more dynamic and energy-rich sources of chemical energy are those associated with liquid water and water/rock interaction.

Fractionation of isotopes which accompanies the cycling of volatile elements also has implications for prebiotic chemistry. Isotopes of the biogenic elements (H, C, O, N) can be fractionated by nonbiological, as well as biological, mechanisms. These must be recognized and understood if fractionations associated with organic syntheses or any biological processes are to be properly interpreted. The major nonbiological processes involve loss of atmospheric components to space. This loss occurs from the top of the atmosphere, where diffusive separation of atmospheric species by mass causes isotopic abundances to differ from those in the bulk atmosphere. Loss to space, therefore, preferentially removes the lighter isotopes and leaves the remaining atmosphere enriched in the heavier isotope. Mixing with nonatmospheric reservoirs can diminish the total net fractionation. Loss to space can occur by thermal escape (for H) and by nonthermal escape mechanisms (for H, O, C, and N). The latter include photochemical processes, such as dissociative recombination, and sputtering by solar-wind pick-up ions. In the latter process, O ions (predominantly) that are produced in the ionosphere spiral around the magnetic field lines of the impinging solar wind, collide very energetically with atoms and molecules in the upper atmosphere, and knock some of them off into space. Measured enrichments of atmospheric D, ^{15}N, and ^{38}Ar are apparently due to these processes.

Compelling evidence for exchange of atmospheric compounds with crustal reservoirs comes from analysis of isotopic ratios in volatiles derived from the SNC meteorites. Enrichment of D to the degree seen in the atmosphere (~ 5× terrestrial) can only occur *via* escape of large quantities of hydrogen to space. That similar enrichment is seen in the SNC meteorites appears to require substantial mixing of water from the atmosphere into the crust. Similarly, oxygen isotopes in water from the SNCs depart from the fractionation line defined by oxygen in silicates, suggesting that the water has not equilibrated with the oxygen in the silicate rocks; because loss of oxygen to space can move the oxygen isotopes off the usual fractionation line, mixing of atmospheric water down into the crust can explain this difference. Given the apparent former abundance of both crustal water and sources of heat, the presence of hydrothermal systems may be a straightforward way of allowing exchange of water between the crust, the surface, and the atmosphere. In addition, there is geochemical evidence for hydrothermal alteration of the SNCs.

Atmospheric Organic Chemistry on Early Mars

The atmospheric compositions of the terrestrial planets early in their histories are poorly known. Much of the work in prebiotic chemistry, both theoretical and experimental, has been based on the view, prevalent in the middle part of the 20th century, that the primitive atmospheres of the terrestrial planets were composed mainly of methane, ammonia, molecular hydrogen, and other reducing gases. The Miller-Urey experiment and subsequent similar work demonstrated that, in such atmospheres, a wide variety of organic molecules can be synthesized by energy sources such as ultraviolet radiation, electric discharges, and shock waves. The products include amino acids and the precursors of amino acids and nucleic acid bases, hydrogen cyanide and formaldehyde.

As a better understanding of the photochemistry of atmospheres has been gained, however, it has become clear that terrestrial atmospheres composed of methane and ammonia will, over geologically short time scales, decompose to a nonreducing mixture of molecular nitrogen and carbon dioxide. Laboratory experiments have shown that the yield of organics from such atmospheres is orders of magnitude less than that from reducing mixtures, suggesting that atmospheric organic chemistry may not have been the major contributor to the organic inventories of the early Earth and Mars.

The scenario for the environment of the early Earth and Mars has been further complicated by the recognition of the so-called faint young sun paradox. Models of stellar evolution indicate that the sun was approximately 30% less luminous than today during the first Gyr or so of solar-system history. This requires increased levels of greenhouse gases in the atmosphere of the early Earth in order to maintain a surface temperature above the freezing point of water, liquid water being taken to be a prerequisite for the origin of life on Earth. Since methane and ammonia, two excellent greenhouse gases, should not have been available in large amounts as discussed above, the hypothesis has been developed that the early Earth's atmosphere contained much higher levels of carbon dioxide than are present today, perhaps as much as 10 bar (10 times the current total surface pressure).

Since photographic evidence for surface liquid water on early Mars is available, a similar hypothesis has been developed for the composition of the primitive martian atmosphere. A 1- to 5-bar CO_2 atmosphere would have kept the surface temperature of early Mars at or above the freezing point of water (273°K) according to some models. Modelling which includes the effects of CO_2 cloud condensation at high CO_2 abundances, however, indicates that it is not possible for the greenhouse effect to keep the martian surface above 214°K with CO_2 as the sole greenhouse gas, no matter how much is present. One possible resolution to the martian greenhouse dilemma, though not the only one, is the presence of more-efficient greenhouse gases as minor components of the early atmosphere. Ammonia or methane could serve this purpose and also increase the efficiency with which organic compounds were synthesized by atmospheric processes.

Organic Synthesis During Weathering

Regardless of the timing of the erosion responsible for surface features, it is likely that liquid water has been present at depth in the crust throughout the history of Mars. Normal geothermal gradients will cross the ice-water transition, and any enhanced heat flow from igneous activity will elevate this transition toward the surface. Contact between igneous rocks and liquid water at low temperatures is a source of chemical disequilibrium which may provide the means for organic synthesis. The major manifestation of this chemical disequilibrium is weathering of the igneous minerals to yield low-temperature alteration products which, for basalt, are dominated by clays and hydroxides. In the case of Mars, based on observation of the surface, it appears that part of the overall weathering process is the oxidation of ferrous minerals to yield ferric minerals. For example, each mole of fayalite (Fe^{2+} olivine) which is oxidized to ferric hydroxides and ferric silicates can provide a mole of H_2. It is conceivable that this H_2 could be coupled to CO_2 reduction to yield simple organic compounds as weathering proceeds. On the other hand, if CH_4 was introduced into an environment consisting of already-oxidized minerals, then coupled redox processes could yield organic compounds. The temperature at which weathering reactions occur increases with increasing depth or heat flow, and at some elevated temperature the processes involved would overlap those which would be considered hydrothermal.

Hydrothermal Organic Synthesis on Mars

Hydrothermal systems are an unavoidable consequence of a geologically active planet which has fluid H_2O at or near its surface. When molten rock solidifies it contracts and cracks. If fluid H_2O is present it will move through the cracks, heat and expand, and the hot, low-density fluid will circulate toward colder parts of the system. The critical point of H_2O is at 221 bars and 374°C, which implies that supercritical H_2O fluid can be encountered in many subsurface settings in planets with active volcanic processes. The heat capacity of any substance approaches an infinite value at its critical point, and this helps to explain why H_2O is such an efficient refrigerating substance for volcanic activity on wet planets. In addition, the density reaches a minimum at the critical point and the compressibility and expansivity (pressure and temperature derivative properties of the density, respectively) approach infinite values. Therefore, the transport properties of H_2O in hydrothermal systems lead to dynamic, rapid fluid flow. Accordingly, if magmatic processes occur on wet planets, the hydrothermal systems which inevitably form will transport heat efficiently and rapidly away to the surface of the planet and on to space.

Given the many lines of evidence for the presence of water at the surface of Mars, at least early in its history, together with the abundant evidence for volcanic activity, hydrothermal systems would certainly have existed within the outer layers of the planet, and may have had surface manifestations as hot springs. In addition, the SNC meteorites show geochemical evidence for hydrothermal alteration, and isotopic evidence for exchange of water between surface and subsurface, plausibly *via* hydrothermal systems. This has several implications for the emergence of life on Mars, including: (1) the enormous impact which subsurface mineral precipitation of carbonates, sulfides and sulfates can have on any attempt to explain the volatile budget of the planet; (2) the possibility of hydrothermal organic synthesis; and (3) the presence of inorganic sources of chemical energy that are provided by these systems and which chemolitho-autotrophic micro-organisms are known to use. Each of these points is addressed below.

Comparison shows that carbon is less abundant at the surface of Mars than at the surfaces of the other terrestrial planets, Earth and Venus. It is possible that, during outgassing of Mars through volcanic activity, large quantities of volatile elements were sequestered in the subsurface as hydrothermally precipitated minerals (carbonates, sulfates and sulfides). Ongoing research is testing this hypothesis to see whether hydrothermal sequestering is plausible, given what is known about hydrothermal systems on the Earth and the composition of martian rocks inferred from SNC meteorites and previous missions. Considerable work in geochemical modelling has focused on Iceland as a partial analog for martian conditions.

Such studies are not limited simply to testing the likelihood that carbonate (and/or sulfate and sulfide) minerals will form; entire assemblages of alteration minerals can be characterized. In turn, these theoretical results, tested against terrestrial analogues, provide guidelines for the types of spectroscopic analyses that will be capable of identifying any hydrothermally altered rocks at the surface of Mars. Such spectroscopic fingerprints of hydrothermal activity, which will be detectable from orbiting satellites, will help to guide the mapping of the surface of Mars and will identify likely locations to send landers for optimum results. This coupling of theoretical results with analytical data collection will be crucial to finding locations which are the most likely to hold hydrothermally altered rocks. This approach should allow a more comprehensive study than a survey of the surface for hot-spring deposits. Although appropriate minerals for hot-spring deposits will be revealed with this approach, these methods will also identify rocks altered at much higher temperatures and pressures that may have been exposed at the surface through erosion, tectonic activity or impacts.

If an atmosphere of reduced gases was short-lived, as atmospheric modeling for Earth indicates, then other pathways for organic synthesis should be explored. Research has shown that heat, UV-radiation, shock waves and ionizing radiation can lead to organic synthesis in the laboratory. Nevertheless, they have shown that there are numerous pathways and energy sources that can lead to the synthesis of organic compounds from inorganic starting compounds. In the case of hydrothermal synthesis, a combination of elevated temperatures and oxidation states buffered by mineral-water reactions provides conditions in which organic compounds might be synthesized. Unlike most prebiotic syntheses, the pathway for hydrothermal synthesis is more likely to be through reduction of CO_2 (or CO) than oxidation of CH_4.

Evidence in support of hydrothermal pathways comes from theoretical studies of the reactions which occur among carbon compounds (organic and inorganic) in geochemical processes. Starting from the compositions of organic and inorganic compounds in geologic fluids, recent studies have examined the extent to which these compounds have equilibrated over geologic time. Many organic compounds and CO_2 are found to have attained metastable (rather than stable) equilibrium states in sedimentary basins and in hydrothermal systems. Significantly, the oxidation states that are attained in these systems are those which allow CO_2 and organic compounds to coexist. These oxidation states are highly reduced relative to surface conditions, even when compared to those in most hot springs, and are generally much more highly reduced than unconstrained conditions imposed on many laboratory experiments. Importantly, there are, in these natural systems, many pathways allowing the transfer of carbon between organic compounds and CO_2. Efforts are currently underway to elucidate the extent to which reactions among organic compounds, as well as those between organic compounds and CO_2, are reversible at the temperatures and oxidation conditions at which natural metastable states exist.

In terms of exploring Mars, or the Earth for that matter, it is necessary to delve beneath the surface in order to identify the extent to which hydrothermal organic synthesis may have occurred. Theoretical studies of hydrothermal systems on the Earth indicate that the greatest potential for organic synthesis is not in systems which are the most obvious manifestations of hydrothermal activity. For example, submarine hydrothermal systems have received a great deal of attention as environments in which organic synthesis may occur. However, the potential for organic synthesis is not greatest at the submarine black-smoker vents at the ridge crests. The combination of temperatures and oxidation states at black-smoker vents favors CO_2 rather than organic compounds. Instead, the potential is much greater in portions of the systems in the flanks of the ridges where temperatures are lower and mineral-buffered oxidation states can be considerably lower. A corollary for Mars is that exploration of hot spring deposits at the surface will not necessarily lead to evidence of organic syntheses. There are good reasons for studying hot-spring deposits on Mars, including the constraints supplied to theoretical modelling of fluid-rock reactions, but evidence for prebiotic organic synthesis might not be found there. Instead, the search should be conducted in deeper parts of the system. Until drilling becomes a real option for martian studies, it will be enormously useful to identify portions of the martian crust that contain deeper parts of fossil hydrothermal systems and which have been exposed at the surface through erosion, impacts, or tectonic activity.

Exogenous Organic Compounds on Mars

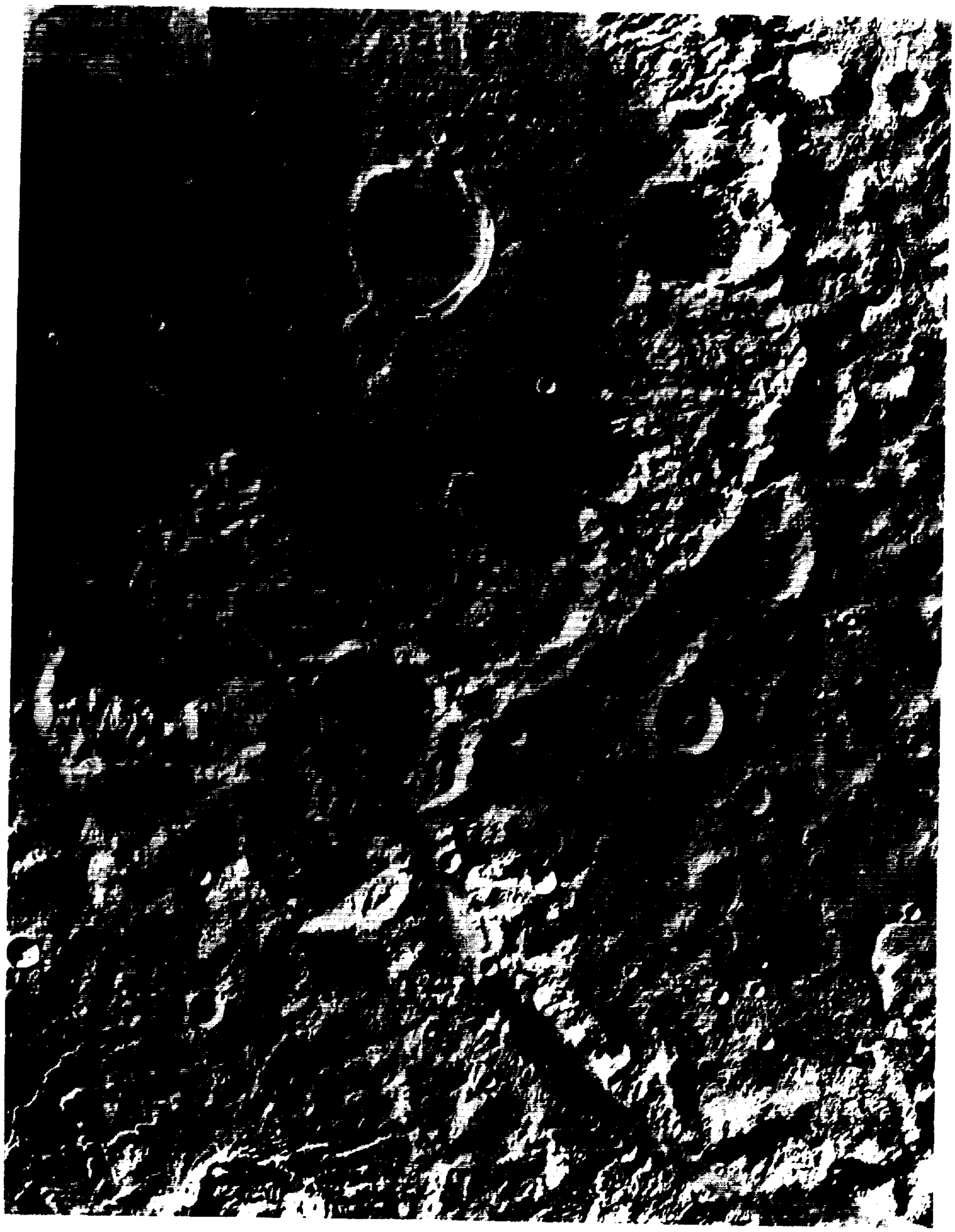
Impact delivery of organics to the early Earth has been suggested as an alternative to atmospheric organic synthesis. Large impactors strike the Earth with enough kinetic energy to generate temperatures sufficient to pyrolyze much of any organic matter contained within. On Mars, however, the lower gravity relative to Earth results in a lower impact velocity for objects of a given mass relative to that on the Earth. This translates into a significantly increased chance of survival for impactor organics delivered by large objects, even in the absence of a dense atmosphere, relative to the chance of survival on Earth. Also, small objects, those the size of recovered meteorites and smaller, are capable of delivering organic matter to the Earth's surface and would similarly do so on Mars. Consequently, impact delivery of prebiotic organic material to early Mars is another possible source of material for martian prebiotic organic chemistry.

Related to this subject is the question of impact transfer of organic matter between Earth and Mars early in their evolution. The SNC meteorites constitute empirical evidence that transfer of intact, moderately shocked material can take place from Mars to Earth, and although the organic content of those meteorites is very low (probably nonexistent), there seems no reason why a reasonably well-indurated, organic-bearing rock could not survive the conditions experienced by the SNCs. Whether the same process could operate in reverse, delivering organics from Earth to Mars, is less likely but perhaps cannot be ruled out. In the event that organic matter is found on Mars, this mechanism would have to be considered as a potential source, but discriminating between this and other possible sources, in any other than a statistical fashion, would not be straightforward.

OBJECTIVES FOR FLIGHT EXPERIMENTS

As a result of the Viking mission, it is already known that organic compounds were not detected in martian soil at two locations. Improved instruments and alternative sites could be considered, but evidence for oxidation – and for continuing oxidative processes – is pervasive. Until more specifically promising samples and sites can be identified, therefore, efforts should be focused on broader examinations of martian surface processes generally and on the history of the biogenic elements specifically. Measurement of isotope ratios in all accessible phases can lead to information constraining mass balances both now and in the distant past. If variations in isotopic abundances over geologic time can be reconstructed, times of origin of specific organic compounds (if any are found) can be estimated and extramartian origins of such compounds might be ruled in or out. The elemental compositions of segregated phases, inorganic as well as organic, can provide information about chemical differentiation of the planetary surface and thus about the chemical environment at times in the past. Conceivable variations in the level of oxidation of the martian surface are of particular interest since they bear not only on the survivability of organic products but, more importantly, on rates of synthesis in the first place.

Stable isotopic ratios in atmospheric species should be measured in the bulk atmosphere and throughout the upper atmosphere. Specific ratios include D/H, $^{18}O/^{17}O/^{16}O$, $^{13}C/^{12}C$, and $^{15}N/^{14}N$. In the bulk atmosphere (to an altitude of ~120 km), compositions of H_2O, CO_2, and N_2 are of interest, water and carbon dioxide being examined separately because differences in their oxygen isotopic abundances will carry information about rates of exchange and thus present-day geochemical dynamics. Above the 120-km homopause, fractionation to the exobase at around 200 km should be measured. At the exobase, atomic oxygen is a significant component of the atmosphere and should also be examined separately. Finally, determination of the isotope ratios of species actually escaping to space would complete a satisfactory examination of the atmospheric isotopes. The significance of observed isotopic variations and, particularly, their historical



Gusev Crater is a ~160 km diameter impact crater that appears to have been depocenter for flows and sediments carried down Ma'adim Vallis, an ~800 km-long channel which originates in chaotic terrain to the south. The lobate, highly channelized unit at the mouth of Ma'adim is interpreted to be a delta deposit that could contain a wide variety of lithologic types, including potentially fossiliferous sedimentary materials. High-resolution images reveal shoreline terraces suggestive of formation by a lake that may have existed here.

development, can be clarified only through consideration of the processes by which species escape to space or are sequestered at the surface. Parameters relevant to these processes must be examined closely.

Continuing study of images of the martian surface has provided a wealth of information pointing clearly to chemical differentiation of the surface, but chemical compositions are known at only two sites. To whatever extent elemental abundances can be mapped on a planetary scale, it will be invaluable in providing information about the system within which any prebiotic organic syntheses occurred. Elemental abundances alone, however, are insufficient to identify materials altered by hydrothermal fluids. Rocks altered at high temperatures and pressures may have elemental compositions which would be difficult to differentiate from unaltered, pristine igneous rocks. In such altered phases, however, the mineralogy (*i.e.*, crystal structure as well as chemical composition) would be vastly different. Depending on temperature and pressure of alteration, chlorites, smectites, serpentines, amphiboles, micas, and other hydrous phases might characterize the hydrothermally altered rocks. In addition, the compositions of many anhydrous phases (feldspars, pyroxenes, olivines, *etc.*) change as a consequence of hydrothermal alteration. As an example, plagioclase in Icelandic rocks becomes enriched in sodium even in systems where fresh water reacts with basalt.

Mineralogy can be determined with increasing precision as Mars exploration moves from orbiters to landers to sample return. From orbit, infrared spectroscopy can reveal the presence of major minerals present in the surface material. As an example, a search could be conducted for silica, carbonates, and other evidence of hot-spring deposits. Surface manifestations of hydrothermal systems, like hot springs, can represent minor volumes of material compared to the magnitude of altered materials in the subsurface. Therefore evidence for hydrothermal systems might be more abundant in regions where the interior of the crust is revealed through erosion, impacts, or tectonic activity.

Landers equipped for IR spectrometry, and X-ray diffractometry/fluorescence can further enhance knowledge of the mineralogical inventory, especially if they are coupled with devices which can obtain samples from outcrops as well as loose material at the surface. Ideally, shallow drilling, of rocks as well as into soils, coupled to X-ray and other spectroscopic analyses will provide much-needed information on the depth of weathering, extent of ground ice or ground water and possible stratigraphic relations among mineral assemblages.

No understanding of martian prebiotic chemistry can be complete without an attempt to detect and quantify organic compounds. Measurement of the amount of organic carbon in various geochemical environments will be crucial to understanding the global carbon cycle on early (and perhaps present) Mars. These environments would include sedimentary basins, in which organics produced by atmospheric processes or delivered by impactors might be buried beneath sediments. Subsurface aquifers, which could either produce organics through hydrothermal processes or perhaps collect and concentrate them by precipitation, should also be examined.

Wherever organic materials are found, quantitative determination of total organic carbon is a minimum requirement. Beyond that, determination of the relative abundances of carbon, nitrogen, hydrogen, and oxygen and their stable isotopes would provide clues to the likely nature of synthetic processes. Following up on those clues, identification and quantitative molecular and isotopic analyses of individual compounds, such as nucleic acid bases, and amino and fatty acids, would be most useful in determining the relative importance of atmospheric, impact, and hydrothermal processes in organic synthesis on early Mars. Each of these mechanisms generates a pattern of species abundances which can, in principle, be distinguished from the others. Organic compounds of ambiguous prebiotic relevance, such as impactor-derived polycyclic aromatic hydrocarbons, could also be useful in this regard.

THE SEARCH FOR EXTINCT LIFE

INTRODUCTION

Because life on Earth appeared early in our planet's history and therefore must have originated relatively rapidly, it is possible that liquid water persisted on Mars long enough for life to begin there as well. Thus, the fundamental question of whether life exists or existed elsewhere in the universe may be answered in our own galactic back-yard. This mandates that we search for a martian fossil record. The current surface environment of Mars is hostile to life as we know it, and an ancient biosphere might have become extinct. The discovery of an extinct martian biosphere would be of immense scientific importance: the demonstration that life originated independently in two places in our solar system would have far-reaching implications for the distribution of life elsewhere in the Universe.

Below is a concept to search for a biosphere which became extinct perhaps a few Gyr ago. The search is naturally allied with investigations of prebiotic chemistry and extant life because all three efforts will be largely chemical studies and because the locations to be targeted on Mars will overlap extensively. Such an investigation inevitably draws heavily on our experience with studies of earth's early biosphere.

EXPERIENCE WITH EARTH'S EARLY FOSSIL RECORD: RELEVANCE FOR MARS

Tectonic activity has altered, concealed or destroyed most of Earth's early crust. Careful regional geologic mapping has therefore been necessary to locate and characterize older Precambrian sequences. Many early Archean aqueous sediments occur typically as relatively thin-bedded units within thick sequences of volcanic rocks. These sequences have been explored for those sediment types most likely to contain fossils. Fossils have typically been found in cherts, which are impermeable siliceous rocks that resist weathering. The best-preserved specimens are found in rocks having fine-grained, stable mineral textures with well-preserved (and/or abundant) organic matter or other reduced chemical species. These samples have been searched for morphological, chemical or isotopic evidence of ancient life, and they have been interpreted in the context of their preservation and paleoenvironment. It is significant that the antiquity of the fossil record (3.5 Gyr) corresponds with the age of the oldest sediments which have been sufficiently well-preserved to have retained conclusive evidence of life. Thus, the antiquity of the fossil record is probably limited by the preservation of rocks favorable for fossil preservation, and life is likely to have appeared significantly earlier than the oldest sedimentary sequences.

Certain concepts have emerged from Precambrian studies which seem relevant to a search for life on ancient Mars. For more than five-sixths of our own biosphere's history, life existed predominantly as single-celled organisms. Thus the most ancient and ubiquitous life form in a putative martian biosphere would presumably have been microbial. Also, mineralization and/or rapid sedimentation which occurs in close proximity to microbial communities will enhance their fossilization and preservation. This is because decomposition proceeds to completion unless the cells have been isolated from decay. Short-term isolation can sometimes occur in high-salinity environments where decomposition by microbial activity has been suppressed; however, long-term fossilization additionally requires entombment in an impermeable mineral matrix. Some of the best preserved examples of Precambrian fossils were probably rapidly encased in primary silica precipitates before decay could occur.

Because multiple lines of evidence (morphologic, sedimentological and chemical -- including isotopic) have been crucial for interpreting Earth's own Archean fossil record, they will probably be required to prove that a prospective martian fossil deposit is indeed biogenic. Our ability to identify the remains of hypothetical martian organisms depends ultimately upon comparisons with extant terrestrial analogs, and such comparisons may prove to be inaccurate. Furthermore, biological information preserved in sediments is often altered or destroyed by biological degradation, elevated temperatures or pressures, or oxidation.

Morphologic evidence includes forms which are visible at various size scales, ranging from microscopic cells to macroscopic microbial constructs, such as stromatolites. "Chemical fossils" include those biologically produced substances which can be conclusively distinguished from nonbiological ones. Most notable among these are distinctive organic compounds (*e.g.*, certain lipids or amino acids), although inorganic substances, such as certain phosphate minerals, can also be diagnostic. Differences in isotopic composition, such as the contrast observed on Earth between sedimentary organic carbon and carbonate, can retain the signature of biological isotopic fractionation.

Fossil evidence can be quite abundant in sedimentary rock sequences which have escaped extensive degradation. One illustrative example is the 600 to 900 Myr-old sequence from Svalbard, an island located midway between Scandinavia and the North Pole. About 25 percent of all carbonates in these rocks contain fossil stromatolites formed by microbial communities. (Note that macroscopic evidence of stratiform or domal laminated rocks is not sufficient to prove microbial genesis. Abiotic structures as various as calcretes, tufas, stalagmites, and even malachite bodies share similar physical characteristics. A role for microbial mat communities must be demonstrated on the basis of detailed petrologic study.) About 25 percent of all fine-grained siliciclastic samples contain organic-walled microfossils. About 5 percent of all siliciclastics contain diverse, well-preserved fossils that have been invaluable for taxonomic studies. About 10 percent of all carbonates contain microfossils; however, more than 50 percent of silicified carbonates contain fossils. Essentially all carbonates and fine-grained siliciclastic sediments that contain organic matter provide carbon isotopic evidence indicating biological discrimination.

The Svalbard rocks offer perspectives which are relevant to the Mars exploration effort. The likelihood for retaining evidence for life in well-preserved rocks of the right mineralogy is high. The best preservation is found in cherts and unoxidized fine-grained siliciclastic rocks, although carbonates also provide important information. The best strategy for finding fossils should combine visual with chemical and isotopic observations. Based on experience with the Precambrian on Earth, the detection of morphological microfossils has an inherently lower probability of success than the detection of chemical evidence, but it offers great rewards if successful. Chemical and isotopic observations greatly improve the overall probability for locating ancient evidence of life. In either case, success rests largely on targeting appropriate lithologies.

Compared to the Earth, the ancient martian crust has been less affected by destructive tectonic forces, thus the discoveries of remarkably abundant microbial remains in Earth's well-preserved Precambrian carbonates and shales are encouraging for Mars exploration. However the fraction of ancient sediments deposited in aqueous environments is likely to be smaller on Mars than on Earth, particularly during the past 3 Gyr. Thus, it should be easier to find well-preserved ancient martian crust, but it will be perhaps more challenging to locate and sample aqueous sediments within crustal sediments. The principal strategy, then, is to locate and analyze aqueous sediments, particularly those that are good repositories for a fossil record.

KEY SITES ON MARS

Life's fundamental requirements for liquid water, energy and nutrients form the basis of a search for sites on Mars which are most prospective for locating a fossil record. If we allow that life might have been initially autotrophic rather than heterotrophic, then it follows that all plausible energy sources which could drive metabolism should be considered. Solar radiation is likely to have been the major, reliable source of energy, but access to it requires elaborate photochemical systems for conversion of physical (light) energy into chemical energy. It is presently unknown whether such systems evolved early on Mars or the Earth. On the other hand, it is conceivable that an early metabolic system may have used sources of chemical energy. Rather than requiring the machinery with which to capture light energy, early microbes could have been chemoautotrophs and perhaps chemolithoautotrophs. Therefore all potential sources of chemical energy that could arise at or near the surface of Mars or the early Earth should be considered.

Thermal-spring deposits

Subaerial thermal-spring deposits have been identified as important targets for locating a martian fossil record because such springs might have been oases in the literal sense, and they also would have provided reduced gases to serve as sources of energy and reducing power for organic synthesis. Thermal-spring waters also can sustain the high rates of mineral precipitation which, on Earth, typically occur in the presence of microbial communities. Volcanic terrains are widespread on Mars, and some include outflow channels of simple morphology that may have formed by spring sapping. The association of such features with potential heat sources, such as volcanic cones or thermokarst, provides evidence for near-surface hydrothermal systems. Minerals most commonly deposited by subaerial thermal springs include silica, carbonates and iron-oxides. Siliceous sediments are particularly favored because they tend to be fine-grained and are relatively stable during post-depositional changes. Organic-rich cherts (fine-grained deposits of silica) provide some of our best examples of microbial preservation in the Precambrian. Although rates of organic-matter degradation appear to be quite high within thermal environments, a great deal of biological information is retained in the macroscopic biosedimentary structures (stromatolites) and biogenic microfabrics of spring deposits. Many primary biogenic features of subaerial spring deposits survive diagenesis (*e.g.*, recrystallization, phase changes). Spring deposits are excellent targets for fluid inclusions, which may preserve samples of original liquid and volatile phases and, potentially, micro-organisms and bio-markers. Such deposits are also prime targets for prebiotic compounds.

Lakes

Lake beds are important targets, because ice-covered lakes might have been sites for life's "last stand" on the martian surface. Subaqueous spring carbonates (tufas) and sedimentary cements deposited at ambient temperatures often precipitate rapidly in the presence of microbial communities. Such deposits form when fresh water emerges from springs at the bottom of alkaline lakes. Mineral precipitation is apparently driven primarily by inorganic processes, although microbial mats may also influence precipitation during periods of peak productivity in areas where rates of inorganic precipitation are lower. Tufa deposits often contain abundant microbial fossils and organic matter. Sublacustrine springs commonly occur in volcanic settings, in association with crater and caldera lakes, and can include thermal deposits. Volcani-lacustrine deposits are frequently strongly mineralized and comprise some of our best examples of well-preserved microbial communities in terrestrial settings

Evaporite deposits

When a lake shrinks or disappears by evaporation, the more-soluble salts can precipitate and capture other constituents. When evaporites crystallize from solution, they commonly entrap large numbers of salt-tolerant bacteria within brine inclusions. Evaporites have been suggested as potential targets for extant life on Mars, although considerable debate currently exists regarding the long-term viability of such micro-organisms within salt. Still, brine inclusions in evaporites may provide excellent environments for preserving fossil microbes and biomolecules. The disadvantage of evaporites is that their high solubility limits them to comparatively short crustal residence times. Consequently, most Precambrian evaporites are known from crystal pseudomorphs preserved by early replacement with stable minerals, such as silica or barite. On Mars, the most likely places for evaporites are terminal lake basins where standing bodies of water existed perhaps intermittently. The central portions of terminal lake basins, including impact craters and volcanic calderas, are potential targets for evaporites on Mars. The typical "bulls eye" distribution pattern for evaporites within such settings indicates that carbonates are normally found in marginal basin areas, with sulfates and halides occurring progressively more basinward. Such basins also might contain fine-grained, clay-rich siltstones and shales. These rock types are significant in that, on Earth, they sequester the bulk of sedimentary organic carbon and other reduced species such as biogenic sulfides. Although these rocks are usually less resistant to weathering than cherts or carbonates, their sometimes high organic contents on Earth emphasize their potential importance on Mars.

Cemented regolith

As surface water percolates downward through soils, more-soluble compounds tend to be dissolved from the upper horizons and redeposited at depth as mineralized "hard-pans" (*e.g.*, calcretes, silcretes). Mineralized soils commonly contain microfossils of the soil microbiota entombed in hard-pans or duricrusts. Mineralized horizons within paleosols may be widespread on Mars and should not be overlooked as potential targets for exobiology. Indeed, images from the Viking landers indicate that, in places, soils are indurated and form surface crusts which are resistant to ablation by wind. Rock varnish, dark coatings observed in arid environments, often reflect biological processes, and therefore should be searched for on Mars.

OBJECTIVES FOR FLIGHT EXPERIMENTS

It will be important to achieve a global perspective of the extent to which liquid water has altered the chemical composition of the martian crust. Elements such as calcium and aluminum respond quite differently during aqueous weathering of igneous rocks. This creates a wide range in the

Ca/Al elemental abundance ratio among the various products of aqueous weathering. Similar, albeit somewhat less dramatic, patterns are also observed for the elements magnesium, sodium and potassium, relative to aluminum. Correlations between the ratios of these elements and other morphological indicators of the activity of liquid water could be informative. Gamma-ray spectroscopy can perform elemental analysis of the martian crust from orbit and thus is important for evaluating elemental distributions on a global scale, although the prevalence of a widespread aeolian layer comparable in thickness to the gamma-ray penetration depth could be a complicating factor. The best information will likely be obtained from areas of aeolian erosion where bedrock is exposed at the surface, and such areas should be targeted for orbital spectroscopy.

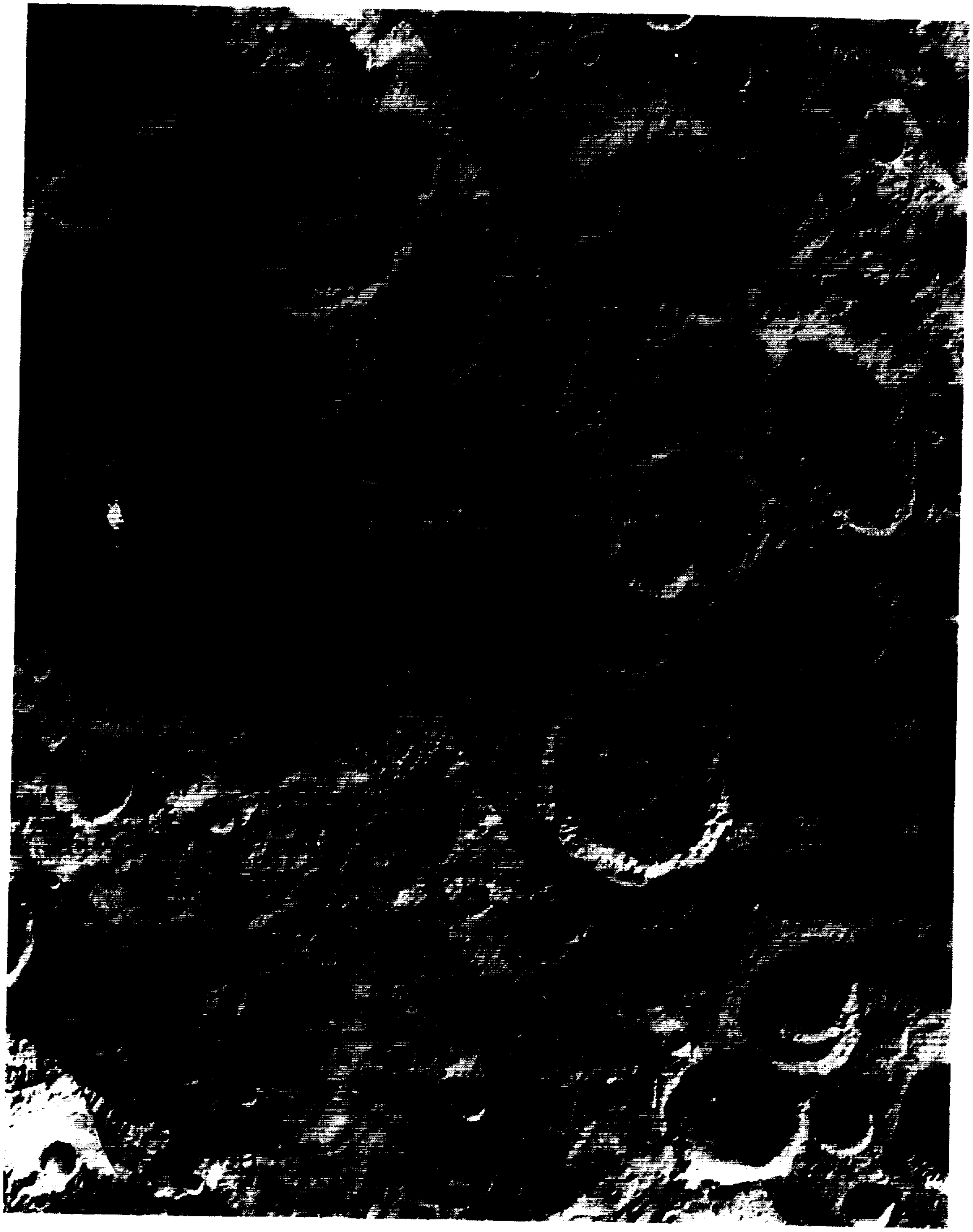
On Earth, high local concentrations of certain elements are particularly diagnostic of biological processes. Phosphorus is notable among these elements; it is a major constituent of bone and its deposition as phosphate-rich rock often reflects the decomposition of sedimented organic matter. Thus, in addition to the ability of phosphate to entomb and preserve fossil materials, an elevated abundance of phosphate minerals might be a key indicator of past biological activity.

A major effort should be made to locate rock types which are favorable for the preservation of fossils. These key rock types include carbonates, phosphates, evaporites, and silica-rich precipitates such as cherts. This effort should be pursued from orbiters, landers or rovers. These key minerals typically have characteristic spectral signatures in the near- and mid-infrared (IR). In addition, a number of diagnostic siliciclastic minerals, including clays, are formed by the aqueous alteration of igneous rocks. These minerals can also be identified using IR spectroscopy. Epithermal hydrothermal deposits have also been detected using airborne magnetometers.

Aqueous minerals that are both fine-grained and diagenetically stable are favored for good preservation. These minerals can be identified in near-IR reflectance spectra or mid-IR emission spectra. The presence of reduced chemical species such as organic matter may also be detected spectroscopically. Because such rocks might be relatively rare at a given landing site, rover-based spot spectroscopy would be useful for surveying and quickly evaluating numerous rocks in order to assess the chemical, mineralogical and petrologic diversity of a site. Imaging at visible and infrared wavelengths is fundamentally important for locating favorable rock types for a chemical or morphological fossil record. Camera capabilities should allow not only panoramic views but also telephoto and close-up "hand-lens" options for evaluating rock textures. Microscopy should be done with a range of light sources, including UV to detect fluorescence. This can provide important information about mineralogy and also be used to search for organic matter. For rocks found to be promising, more detailed analyses of their elemental composition, mineralogy and volatile contents are warranted. Because weathering and other processes can alter rock surfaces, an accurate assessment of mineralogy or volatile content might require that rock interiors be sampled. Thus, a drill or other device must be developed for penetrating rocks.

SAMPLE RETURN

Virtually all investigators in the Precambrian paleontology community believe that definitive discovery of martian fossils will require observations made in Earth-based laboratories. Thus, the exploration activities described above might constitute only a critical prelude to the actual revelation itself. The need for sample return is based on the conviction that fossil evidence will be challenging to obtain, and that the analytical capabilities of Earth-based laboratories are indeed much more formidable than flight instrumentation. Secondly, the latest technologies can be applied and new methods can even be developed and tailored to the task. Perhaps most importantly, the fullness of human perception, flexibility and insight can be brought to bear on returned samples.



Parana Vallis, in the Margaritifer Sinus region of Mars, is located within what has been interpreted to be an ancient paleoloake basin. The presence of complex dendritic channel systems surrounding the basin suggests a prolonged period of hydrologic activity. The absence of younger lavas covering the basin floor suggests that fluvial-lacustrine sediments could be at or near the surface and accessible to landed missions.

THE SEARCH FOR EXTANT LIFE

INTRODUCTION

Two relatively recent insights into planetary evolution, *i.e.*, the antiquity of organisms on the Earth, and evidence suggestive of a "wetter, warmer" environment on early Mars, coupled with recognition of the ubiquitous presence of organic compounds in the cosmos, lend credence to the speculation that Mars may have developed a biota in its early history. If an origin of life did, indeed, occur on Mars then one can logically ask whether the organisms were able to evolve over the subsequent millennia of martian history, allowing them to retreat into special environmental niches, where metabolism, growth or simply survival is possible. It is this possibility that sets the stage for the search for extant life, the discovery of which would be of first-order significance for the science of biology. As Lederberg pointed out almost 35 years ago, "...'life' until now has meant only terrestrial Life" and, unlike the case for the physical sciences, there are few universal principles that can be applied to biology. Comparison of basic terrestrial biological attributes, such as cellular structure and biochemical constituents, with those of an extraterrestrial life form can lead to deeper understanding of what are truly fundamental attributes of living things.

An added dimension to the search for extant life on Mars is that, from a programmatic point of view, plans for human missions to Mars must take into account whether or not Mars is a "dead" planet. At the present time, with the limited information we have about life on Mars, human missions will almost certainly be encumbered by elaborate and costly measures to assure that both Mars and Earth are protected from biological contamination. If future missions, with appropriate payloads to search for extant life, continue to find no evidence for martian organisms, mission planners will almost certainly be less constrained by considerations of planetary protection. Conversely, if such experimentation reveals the presence of extant life on Mars, it is likely that human missions will be delayed until this biota is characterized.

We begin with the definition of extant life as that biomass that is now either growing or surviving in some dormant state. Three distinct types of evidence for extant life may be postulated. First, growing life could be recognized directly, *via* the detection of metabolic activity, probably practicable only within an appropriate niche where growth is occurring. The major condition to consider here is that of liquid water, which, while generally absent on the surface of the planet, may have transient or even long-term stability at certain sites. The second type of evidence involves dormant life, which may be spatially or temporally separated from a hospitable niche and in a nongrowing, but surviving stage, from which it could in principle be resuscitated for detection. Finally, we consider the possibility of nonliving indicators of extant life which would be found as geochemical tracers (organic or inorganic remnants or products) in recent environments that are hostile to life, but which would be indicative of life existing in other niches. Such indicators might include biogenic gases, biogenic minerals, or complex organic molecules indicative of living systems. Clearly, then, a major item of importance in the search for extant life is the location of sites that are most likely to favor finding life or an indicator of it. These will include both protected environments or niches favorable to life, or those places where evidence of hidden life may be found near to the surface of the planet.

CRITICAL REVIEW OF VIKING BIOLOGY EXPERIMENTS

To date, the only attempts at probing the surface of Mars for the presence of extant life were carried out on the two Viking landers (discussed earlier) in the late 1970's. Experiments were conducted that would have detected any of the three types of evidence for extant life considered above (metabolically active, dormant, nonliving indicators). The logical, and perhaps only workable, assumption was that the properties of any extant martian life form should be similar to terrestrial living forms. Given the uncertainties of testing for an undefined life form, and the constraints of mission design, the Viking life-detection experiments appear logical and proper. In essence, the rationale involved the detection of organic molecules (bio-indicators), and metabolic activities of photosynthesis or respiration (by metabolically active or dormant organisms). Analysis of the Viking life-detection experiments, when taken together with all of the other Viking results, have generally been interpreted as indicating the absence of extant biology at the two sites that were examined.

Over the intervening years, a number of arguments have been raised regarding both the validity of the Viking data and the conclusions that were drawn from them. Some workers, for example, have maintained that the results of the Viking Labeled Release experiment were consistent with the presence of indigenous organisms on Mars and have argued against the prevailing interpretation of the Viking biology experiments. While results of this and other experiments clearly indicated the occurrence of chemical reactions on Mars, the inability to distinguish biological from chemical processes clouds the issue. This is perhaps a consequence of the unexpected chemical activity of martian soils, suggestive of a variety of chemical oxidants, combined with differential temperature sensitivities of the chemical reactions they catalyze. As argued earlier, further study of the Viking results using simulated martian materials and environments is clearly warranted.

Another issue raised regarding interpretation of the Viking biology experiments concerns the constraints under which the metabolism experiments were conducted. Incubation conditions (*e.g.*, temperature, light, moisture, duration of incubation) that differed from natural conditions might have had negative effects on indigenous species adapted to local conditions. On the other hand, unnatural incubation conditions could in many cases be viewed as logical attempts to provide more optimal conditions for the recovery of dormant organisms. An even more significant potential shortcoming of the metabolism experiments was the lack of consideration of the full range of potential resources (*e.g.*, energy sources and electron acceptors) that could be utilized by the extant biota. For example, anaerobic respiratory metabolisms have been proposed that can be rationalized for surface, and especially for subsurface, geothermal habitats. The Viking biology payload was selected and developed with very little knowledge about the possible surface chemical and physical resources and conditions to be encountered. An extremely important and valuable lesson derived from these Viking experiments is that the preferred strategy for seeking metabolic evidence of life is first to characterize the conditions and resources in environments where there is reason to believe evidence of metabolically active life may be found.

Geochemical approaches, such as attempts to detect organic molecules typical of life, are more generic, as they do not assume specific types of metabolism. For example, although not a life-detection experiment *per se*, the pyrolysis GCMS experiment of Viking would have yielded convincing evidence of life if the proper molecules had been detected. This experiment, however, has been criticized for its insensitivity: the lower detection limit was judged to be on the order of 10^6 bacterial cells equivalents, a number which is frustratingly large. It is fair to say, however, that few sites exist on Earth where positive results would not be obtained. Given the knowledge gained from Viking regarding the water of hydration released during pyrolysis, the advancement in GCMS technology, and new developments in the amplification of specific molecules of life, more sensitive detection of organic compounds should now be possible.

Perhaps the most valid critique of the Viking experiments is that they were conducted at the wrong place (and/or possibly time) to detect biology on Mars. All evidence from experiments done at the two landing sites suggests a cold, arid surface environment, apparently suffused with oxidants capable of degrading organic compounds. Future studies must certainly seek sites that are wet (and thus warm) and/or protected from oxidants if extant life is to be detected. Viking results indicated that if biology exists on Mars it does not imprint an obvious mark on the atmosphere, such as has terrestrial life (*e.g.*, abundances of methane and nitrous oxide dramatically out of equilibrium with an oxygenic atmosphere). There appears not to be a dominant global biogeochemical cycling of major elements. This does not preclude more circumscribed biogeochemical cycles in either local or widespread environments that are more hospitable, isolated from the harsh surface environment. Whether these actually exist on Mars is unknown, but if there are niches capable of supporting martian life, it is of paramount importance that they be identified and probed for the presence of living entities.

POSSIBLE HABITATS FOR EXTANT LIFE

Finding appropriate niches for metabolically active life on Mars is tantamount to finding sources of liquid water, however intermittently water may become available. Since liquid water cannot now exist as a stable phase on the surface of Mars, even as eutectic brine solutions, the critical factor in the search for extant organisms is to bring to bear techniques for the identification of martian sites where liquid water either exists under isolated conditions, or where it can exist transiently for organisms capable of an existence that is punctuated with periods of dormancy with no available liquid water.

In recent years, several scenarios have been advanced for specialized environments on Mars within which biological activity might be maintained. One such example that has been proposed identifies subsurface sources of liquid water as possibly affording environments for extant biology on Mars. In this scenario, geothermal sources produced by volcanic activity could provide water at some depth and, at the same time, provide volcanic materials such as H_2, CO, and H_2S, which could serve as reductants for nonphotosynthetic, chemoautotrophic metabolism. As discussed above, the Viking biology payload did not include experiments designed to test for this type of metabolism.

The idea of subsurface environments for extant biology is strengthened by evidence suggestive of hydrothermal activity on Mars in the past. However, whether Mars is still geologically active is not yet determined. Nevertheless, as part of the exobiology strategy for extant life, it is crucial to investigate this possibility because of its importance to the question of possible localized hospitable niches on Mars. There may well be subsurface regions where liquid water is available, and where the local conditions might support the growth of an indigenous biota. There may even be small surface features, like vents or fumaroles (undetectable in the Viking imaging and thermal-mapping experiments), where subsurface volcanic sources may be releasing water and reducing gases into the local environment, and providing sources for metabolic activity. In future missions, discovery of such surface features will require very-high-resolution imaging and thermal-mapping capabilities. Also, if methods with high spatial resolution could be developed for the identification of gaseous atmospheric constituents from orbit or at the surface, this technique could be extremely useful in delineating regions that might support the kinds of metabolism envisioned in this scenario.

Another class of potentially suitable environments is represented by more widespread groundwater or aquifer systems that would be maintained in liquid form by core geothermal heat, but not be involved with surface or near-surface geothermal activity. To find such systems would require drilling, but without further information about the global distribution of water and ice, as well as the areal and depth distribution of the presumed oxidants on Mars, it is difficult now to estimate the depths to which such drilling would be needed, or to locate sites feasible for drilling operations.

An additional potential niche for extant life is illustrated by an ecosystem containing bacteria and algae that can be found within certain rocks found in the cold, dry valleys of Antarctica. The habitat for these organisms (cryptoendolithic autotrophs) consists of porous, translucent rocks, in which growth of organisms occurs a few mm below their surface when sufficient water is absorbed by the rocks from surface ice and snow as a consequence of warming during sunlit portions of the day. However, arguments have been raised against this scenario, which at least superficially appears to be applicable to Mars. First, that Mars is considerably drier than the dry valleys of Antarctica; second, that, under current martian atmospheric conditions, melting of ice/snow could not supply liquid water to the interior of the rocks; and finally, that the rocks on Mars appear to be opaque rather than transparent. Note that this does not imply that there has not been in the past, or could be in the future, conditions where liquid water could in fact be intermittently supplied to such endolithic-type niches. Some speculative evidence indicates that such might in fact be the case; aspects of the large-scale morphology of the surface suggest that either liquid water or abundant surface ice might have been present, and theoretical calculations of the history of Mars' obliquity indicate that conditions at some times might be conducive to the presence of liquid water. Given current Mars conditions, a search for endolithic microbial communities would be a search for dormant microbial biomass in rocks found in regions where water might have been stable in a past geologic epoch.

Still another class of potential sites for extant life consists of those where organisms continue to survive, although growth or metabolism is not apparent. These organisms are distinguished from the temporally dormant organisms by longer-term separation from an environmental niche hospitable to growth. For example, it is known from terrestrial samples that, as evaporites crystallize out of solution, halophilic bacteria can be entrapped within developing salt crystals and it has been suggested that active metabolism may occur within brine inclusions that are sometimes found in such crystals. Furthermore, viable micro-organisms have been isolated from salt crystals that are thought to be 200 Myr old. Assuming these findings to be true, a scenario can be proposed that as Mars lost its surface water over geologic time, organisms retreated into saline environments and that some halophilic organisms may still be surviving inside the resulting evaporite crystals. A strategy that has as its objective the search for such halophilic organisms on Mars must begin with global reconnaissance aimed at locating sites with potential for evaporite deposits.

A somewhat similar scenario for extant biology on Mars is based upon the microbiology of permafrost regions on Earth, where evidence has been presented that organisms can remain viable for very long periods in ice obtained from these sources. Thus, permafrost and ground ice on Mars might be possible sites for extant biology. Current models of ground ice on Mars suggest that it would be unstable at latitudes below 40^{o}, thus restricting to higher latitudes potential targets for testing this scenario. Until more is learned about ice contents of candidate features and their global distribution on Mars, serious attention to this scenario also must begin with global studies (*e.g.*, water distribution and history, and climate variations).

Another class of sites includes those inhospitable to life even in a dormant state, but which might contain nonliving indicators of extant life. For example, environments where water has flowed over the surface of the planet in the relatively recent past are of great interest. If subsurface life is abundant, then these outflows might be expected to have deposited molecules indicative of extant life, either in the form of organic carbon or as minerals characteristic of living systems. While one cannot estimate with precision the age of noncratered fluvial water features, the possibility that some are relatively young, and therefore of potentially high value in the search for nonliving indicators of extant life, should not be dismissed.

As a final point with regard to the search for extant life, we note that routine monitoring of key atmospheric gases indicative of life may pay high scientific dividends. In atmospheres that are otherwise oxidizing in nature, some reduced gases, such as sulfide or methane, are almost exclusively indicators of either living ecosystems or hydrothermal activity (volcanism). Detection of any of these gases would then argue for further monitoring of possible spatial and/or temporal fluctuations in their abundances. Furthermore, analysis of gas inclusions in polar cores could yield data on such reduced gases that would point towards future analyses of their sources and sinks. Analysis of stable-isotope ratios might discriminate between biological and chemical sources for these gases.

In fact, from the standpoint of exobiology, no search for evidence for life on Mars would be complete without a thorough investigation of the martian polar caps and layered deposits. Since these deposits are collection and preservation zones for material from all around the planet, they may be among the most efficient places on the planet to search for evidence for life. (Recent studies have recovered culturable micro-organisms from polar ice deposits on Earth.) A major objective for such a search would be to examine an outcrop of exposed layered deposits within one of the polar caps. The examination of old, previously deposited material could provide important information concerning physical and chemical environments that existed during Mars' past history, and the stratigraphy of these deposits could provide information on how the martian environment changed through time. Key observations to be made would include a thorough examination of ice and dust deposits at a microscopic scale for morphologic evidence for biologic activity, as well as detailed chemical analyses of the polar deposits for possible preserved biosignatures.

From the discussion above, it is evident that several hypothetical alternative niches for life on Mars have been suggested in the exobiological literature. As of this writing, however, these remain to be located and characterized. Thus, the initial thrust of the strategy for extant life on Mars must be to determine whether or not these environments actually exist. Only with the acquisition of this fundamental information will it be reasonable, from the point of view of extant biology, to probe such putative environments with landed instrumentation.

OBJECTIVES FOR FLIGHT EXPERIMENTS

From the perspective of experimental strategy, the search for extant life can be broken down according to the nature of both the putative life form and its likely habitat. The objective in each case is the location and characterization of sites where either the biota itself exists or a signature characteristic of it may be found. This leads to definition of several types of site.

Sites where active life may exist

The approach in this case can be divided into three phases. The first phase involves remote sensing through imaging, and spectral and thermal analysis using the highest spatial resolution possible, in order to discover whether sites might exist that could support a living system (*i.e.*, warmer, wetter, possessing appropriate chemical resources). The second phase involves landed instrumentation, targeted to sites thought to be compatible with a biota on Mars. The purpose of analyses during this phase is to seek geochemical evidence in support of the presence of biota, and especially to characterize further sites selected on the basis of remotely obtained information during the first phase. Geochemical analyses would seek information on the presence of organic carbon, and if found, its elemental and isotopic composition, as well as specific molecular identities. Inorganic geochemical analyses would be performed to permit recognition of the relative abundances of elements which might have been altered by metabolic processes. Measurements pertinent to characterization of possible biological niches would include analysis of water abundance, temperature, elemental composition (including biogenic elements), electron donors and acceptors which might drive metabolism, hydrated minerals, chemically reactive atmospheric constituents, and "oxidants". Should these measurements confirm the possibility of potential environmental niches for biology, the third phase would then follow, requiring sampling from these sites and carrying out critical biological experiments designed to test for metabolic activities or to recover organisms adapted to those particular environments. For this phase, sample return missions would provide the greatest flexibility and data return, but sophisticated large landers incorporating well-conceived biological payloads could perform some of the crucial experiments *in situ*. This overall strategy is similar to that taken by biologists (microbial ecologists) trying to characterize life in terrestrial environments.

In consideration of the possibility that life forms might inhabit sites which are only intermittently wet, observations that aid in understanding when and where liquid water might have been present on the martian surface over geological time would also be useful.

Habitats that might support dormant life

The approach here follows the assumption that dormant life (at least microbial) might be dispersed globally, but would only survive in the absence of oxidants. Particular locations of interest for survival of dormant organisms include permafrost and aqueous mineral deposits, such as evaporites. On landed missions to any site, geochemical evidence of a dormant biota in samples free of oxidants would be sought. More speculatively, methods for growth-based amplification of dormant organisms could be attempted, though broad assumptions about their metabolic capability would have to be made.

Sites that might yield geochemical information about extant life in another location

Two different approaches are envisioned. The first is to locate sites where liquid water may have been in relatively recent contact with subsurface water reservoirs. This would involve global reconnaissance to determine surface features consistent with flowing water in the geologically youngest regions. Such sites might represent places where geochemical evidence of subsurface life might be sought, as described above. The second approach is to sample polar ice as a global trap for biosignatures. These could consist of gases, which might integrate biological metabolites (*e.g.*, oxidized or reduced gases) produced at specific, dispersed and/or temporally intermittent (and thus difficult to locate) sites associated with metabolically active microbial communities, or solid particles, which might bear chemical or morphological evidence of biotic activity.

OBSERVATIONS/MEASUREMENTS REQUIRED FOR EXOBIOLOGY

The following discussion includes measurements required at global scales, at local specific sites, and by means of sample return, in order to understand and explore prebiotic chemistry, possible extinct life, and possible extant life. An important principle underlying the proposed strategy is that it is essential to understand the martian environment before deploying biologically specific experiments. In what follows, where specific instruments are mentioned, these should be regarded as illustrative and based on current technology; they should not be taken as excluding the possibility of new approaches and technologies.

ORBITAL EXPERIMENTS

The primary focus of global-scale measurements is to characterize and select sites having exobiological interest. The emphasis should be on estimating the size of global reservoirs of volatiles such as water, carbon, nitrogen, etc., and also on assessing the global consequences of the action of liquid water. In addition, sites are to be identified where deposits might have preserved a record of the early environment, including, perhaps, a record of an ancient biosphere. This leads to an approach that rests heavily upon the search for (a) near-surface water, in either liquid, solid, or bound form, and (b) mineralogy and morphology indicative of the presence of liquid water or of present or past aqueous mineral deposits exposed at the surface. In general, measurements are not specifically assigned to prebiotic chemistry, extinct life, or extant life because, to a great extent, the required measurements, and site selections, cross over among the several topics and are not distinct to any single one. Specific observations or measurements are as follows:

Global geologic mapping

Essential baseline information for any detailed exploration of Mars consists of global imaging at an appropriately high resolution (about 10 m, with selected sites imaged at about 1 m resolution) combined with corresponding topographic data. Stereo imaging would greatly enhance the interpretation of geomorphic features and topography, and is useful as an adjunct to laser altimetry. Not only is this information required for site selection and mission planning, but geomorphologic evidence is still a key guide to the evolutionary history of specific regions of the martian surface. In particular, topography is necessary for defining the drainage patterns that have controlled the depositional environment at different sites. Consequently, a high-resolution camera and an altimeter are required.

Ages of surfaces

An important aspect of site selection based upon surface imagery in the visible range is understanding the age of the particular site that will be sampled. For example, the search for extinct life would focus on older sites, while that for extant life would focus on the younger sites. Using cratering chronology and other relative dating methods, appropriate relative ages can be determined. Imaging of specific locations at 10 m resolution would provide the required information. Note that placing this relative chronology on an absolute age basis will require highly sophisticated landers, or possibly sample return missions.

Globally mapped mineralogy

For the minerals of exobiological interest, that would be indicative of the presence of water-deposited sediments or hydrothermal systems, this can best be done with a mid-infrared spectrometer capable of measuring thermal emission between about 5 and 50 μm. Spatial resolution should be the highest possible consistent with global-scale reconnaissance (*e.g.*, a few kilometers), supplemented by higher-scale resolution of sites of potential interest (*e.g.*, better than 0.1 km).

Globally mapped elemental abundances

Global characterization of elemental abundances, particularly for the rock-forming elements, is a prerequisite for understanding the local-scale abundances, mineralogy, and evolution of the surface. For example, ratios of elements such as Ca/Al can be used to help identify sites where aqueous alteration of the crust might have created carbonates or clay-rich deposits. Also, elemental abundances might indicate where hydrothermal processes have played a role. Although high spatial resolution would be of immense value, measurements are limited to global scale by technique. Using gamma-ray spectroscopy, mapping can be done with a resolution equal to the altitude of the orbiter, which would be approximately 300 to 500 km.

Globally mapped near-surface water

Water in this context includes liquid water, water ice, and physically adsorbed or chemically bound water. The former might occur on small spatial scales when activated by heating as a result of volcanism, impact, or other processes. Ice in permafrost regions is a possible site for finding non-living evidence of recently living organisms, as well as a potential source for transient occurrences of near-surface liquid water. IR spectroscopic evidence for chemically bound water would usefully complement spectroscopic evidence for surface occurrences of aqueously altered lithologies. Near-surface water can be mapped on a global scale at 300-500 km resolution using neutron or gamma-ray spectroscopy.

Regions of high heat flow

An expected surface expression of hydrothermal systems and/or areas of high heat flow would be elevated surface and near-surface temperatures. These could be mapped globally using either thermal infrared or microwave observations. In either case, some wavelength measurements would be required, as would high spatial resolution. Again, the spatial resolution should be consistent with the ability to obtain global maps, and higher spatial resolution should be obtained for selected sites. The lowest useful resolution would be of the order of 100 km, while regions of interest should be mapped at 10 m resolution.

Ratios of atmospheric stable isotopes

These are of value in understanding the evolution of the volatile-element reservoirs and in distinguishing biological from nonbiological influences on isotopes. Measurements of D/H, $^{18}O/^{17}O/^{16}O$, $^{13}C/^{12}C$, $^{15}N/^{14}N$ in the bulk atmosphere, in the region between the homopause and the exobase in the upper atmosphere, and in species escaping to space, are required. Observations of properties relevant to escape processes are also important, in order to understand the context of the isotopic data, as are the ratios for elements of non-biological interest such as $^{38}Ar/^{36}Ar$ and $^{22}Ne/^{20}Ne$. The isotopic ratios would require a mass spectrometer, while the related information would require instruments of the type that would fly on a Mars aeronomy orbiter.

Regions of subsurface water

At depths greater than can be explored by neutron or gamma-ray techniques, liquid water can be detected using active and/or passive microwave techniques, especially EM sounding. Instruments that can detect the frequency response of the subsurface might be able to show the characteristic behavior of liquid water, possibly down to depths of kilometers.

Degree of mineral crystallinity

For clays, the degree of crystallinity can be used as an indicator of the intensity of chemical weathering. This may be detectable from orbit using reflectance spectroscopy, covering the wavelength range of 0.3-3.0 µm. Again, coarse-scale mapping of global properties, followed by higher-resolution observations of specific sites would be of most value.

Trace gases

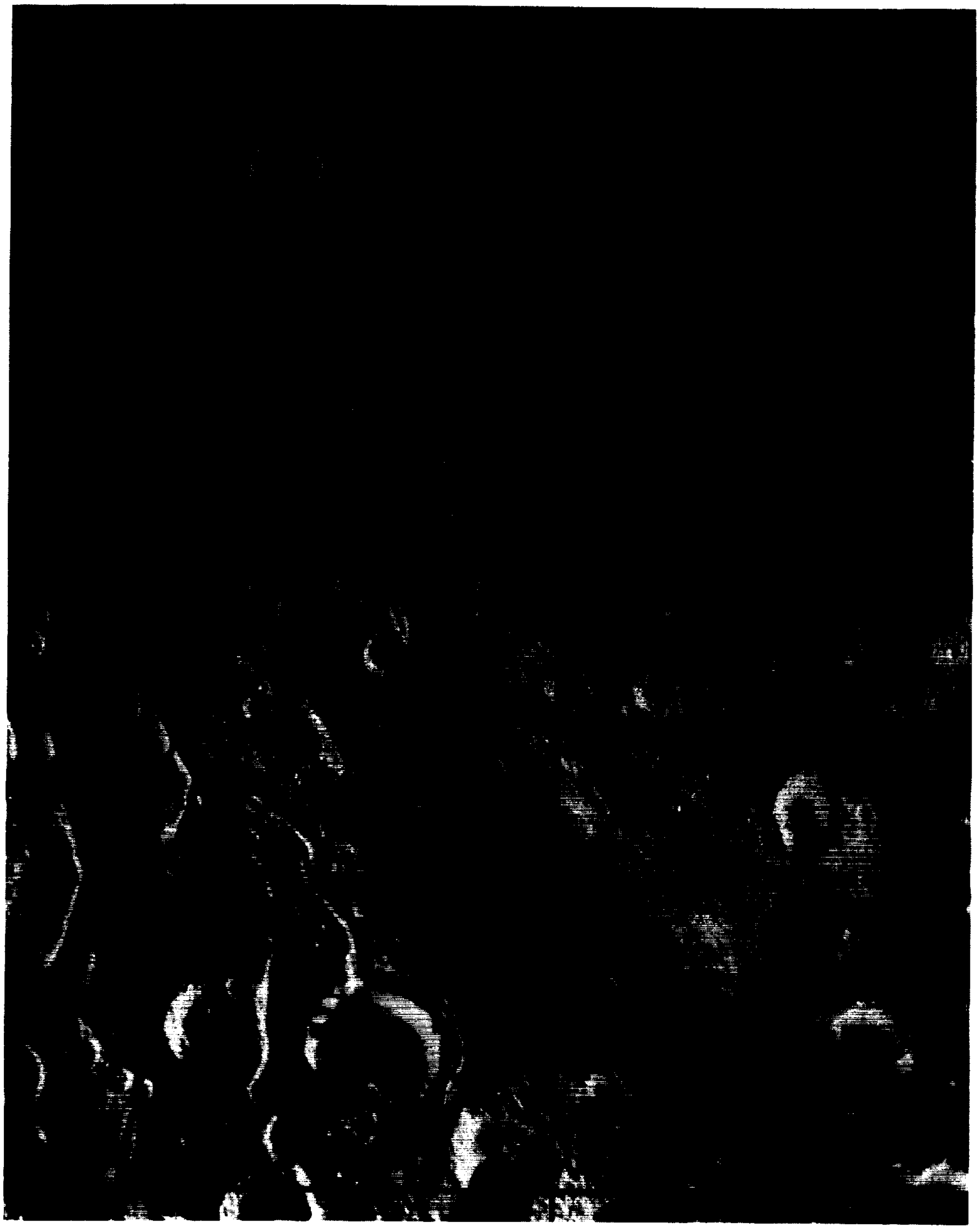
Methods for determining trace atmospheric constituents, particularly if these can be made to estimate near-surface constituents, could provide clues to geothermally active areas and possible subsurface regions of biological activity. Biologically important trace gases like H_2, H_2S, CH_4, SO_X, NH_3 and NO_X are of particular interest in this connection.

LANDED EXPERIMENTS

These refer to *in situ* measurements or observations made by landers or rovers placed on the martian surface. Such observations are needed for specific sites in order to characterize surface chemistry, local geological processes and biological potential.

Preservation and texture of surface rocks

Even with careful site selection, rocks preserving a record of either extinct or extant life may be rare at a landing site, and the same is likely to be true for prebiotic chemical evolution. Consequently, a detailed assessment of rock diversity at a landing site is a necessary early step in the search for either extinct or extant life and is also of



The location of the Pathfinder landing ellipse on Chryse Planitia near the terminus of Ares Vallis outflow channels. This site is considered to be a lithologic "grab bag", containing materials derived from a variety of geologic sources, including potential thermal-spring deposits formed in association with chaotic terrains upstream.

importance in the study of prebiotic chemical evolution. Imagery with sub-mm spatial resolution would be required, thus putting a premium on mobility in order to bring the instruments as close as possible to the target rock. Proper characterization of rocks at a landing site would require mobility within a 10- to 100-m radius of a lander. Regional characterization would require mobility on a multi-kilometer scale.

Elemental abundances of surface materials

In addition to imagery, chemical characterization of the materials at a local site is fundamental. Of interest are the elemental abundances in surficial deposits of fine materials and in rocks. This would focus on the rock-forming elements and carbon and can be done with X-ray fluorescence spectroscopy or alpha-proton-x-ray experiments. Some data on major rock-forming elements can be obtained by means of gamma-ray spectroscopy, coupled with data on naturally radioactive elements and hydrogen, *i.e.*, water. Sensitivity should be of the order of 0.1 wt%. Again, an understanding of the diversity of composition among surface materials will be of major importance, particularly in the assessment of aqueous chemical activity and the search for evidence of extinct or extant life.

Near-surface water abundance

Because of the intimate connection between water and any plausible martian biology, it will be of importance to determine the abundance of hydrogen at any sites to which we obtain access. In most cases, this water will be present in chemically combined form as a hydrated lithology, though it may be possible to find a location where subsurface ice is accessible by drilling beneath a landing site. Alternatively, penetrators may be used to probe beneath the martian surface. Hydrogen abundance can be determined using either passive neutron or gamma-ray spectroscopy or pulsed-neutron gamma-ray spectroscopy, as is used for logging oil wells on Earth. These techniques detect hydrogen within about half a meter of the detector.

Mineralogy of surface materials

Materials that have been altered by hydrothermal activity or weathering sometimes have elemental abundances that are very similar to the unaltered materials. For this reason, specific determination of mineralogy is important in the search for evidence of aqueous processes and for potentially fossil-bearing lithologies such as carbonates, cherts, evaporites or phosphates. This can be done using an infrared spectrometer to do a quick survey of the materials at a given site (with ability to isolate specific small-scale features on the surface, for example with a spot size 1 cm across at several meters distance from a lander), followed up by x-ray diffraction/fluorescence on individual samples. The latter step may require excavation of samples from the interior of rocks. An additional goal of mineralogical investigations on the martian surface is the search for minerals that might have been produced as a result of biological processes, such as phosphates, manganese oxides, and certain carbonates.

Distribution of the surface oxidant

It is important to map the distribution, in three dimensions, of the oxidant(s) identified on the martian surface by the Viking mission. The goal will be to find oxidant-free regions, either at depth in the regolith or at locations where pristine material has been exposed too recently for the oxidant to be present. On a microscale, one possible oxidant-free environment might be the interiors of aqueously altered sedimentary rocks. The first step in determining the distribution of the oxidant(s) is clearly to define its/their chemical nature. This can be achieved by deploying on the martian surface a series of sensors designed to be sensitive to specific oxidants. Probing the vertical distribution of the oxidant(s) will presumably require drilling into the regolith, whereas determining the horizontal distribution will probably involve some kind of compound-specific analysis whose character will depend on the chemical nature of the oxidant(s). Ideally, a chemical signature would be sought whose global distribution could be determined from orbit.

Physical/chemical characterization of the microenvironment

To understand the conditions for survival of putative extinct or extant life forms, a number of physico-chemical measurements must be made. These include assaying the available chemically reactive species in the upper surface, as well as the nature of the environment when moistened or wetted, including pH, Eh (oxidizing potential), ionic strength, presence of micronutrients, and other aspects of the soils and soluble minerals.

Stable isotopic measurements of surface materials

Determination of stable-isotope ratios for the biogenic elements (C, H, O and N) in surficial mineral deposits, *e.g.*, evaporites, provides an additional constraint on volatile history and reservoirs. However, such measurements would probably require significant sample preparation prior to mass spectrometry.

Presence of organic carbon

A stepwise approach is preferred. At the first level, a procedure for quantitative analysis of organic (= noncarbonate) carbon is needed. A system employing a reactive carrier gas and a carbon-sensitive detector should be adequate. Additional information could be obtained by employing temperature-programmed techniques that provided information about temperature of pyrolytic release or combustion and about energy produced or consumed by such processes.

Elemental and isotopic analyses of bulk organic material

If any organic material is found, it is likely that characterizable molecules will be rare relative to total organic carbon. Moreover, most techniques of molecular analysis are applicable to substances with particular levels of polarity or types of functional groups, and these will not be known in advance. For both of these reasons, a second stage of organic analysis should focus on the elemental and isotopic composition of bulk organic material. The elemental information, in the form of atomic ratios, will allow optimization of subsequent molecular techniques, and knowledge of isotopic compositions (for nitrogen and hydrogen as well as carbon) will be of immediate and independent interest, since they will provide information on the origin of the organic matter. A robotic variant of the conventional laboratory procedure of combustion, gas purification and mass spectrometry seems the most likely approach.

Molecular identity of organic carbon

Spectroscopic instruments capable of providing information about bond types and even specific molecular identities should be flown when evidence for analyzable species is found. Resulting data would yield important information about synthetic mechanisms, in the case of prebiotic evolution, and about possible biomarkers, in the case of extinct or extant life. Key compound classes for which evidence should be sought include lipids, amino acids, and carbohydrates. The analytical system should include chromatographic or other techniques of separation. New technologies like the polymerase chain reaction, and variations of it, may provide a basis for amplification of genetic material (and thus increasing sensitivity), and with appropriate experimental design, might provide simple automated tests which would be highly informative. While these approaches involve major assumptions about the nature of martian life, they are becoming automated and miniaturized to the point that they should be included in such studies.

Biomarkers at the poles

With respect to geochemical measurements at the polar ice cap, coring, sampling and detection of entrained gases (CH_4, H_2, H_2S, etc.) would be important. If life ever exerted a global biogeochemical effect on the planet, and if the polar ice cap has trapped this record, it should appear. Similarly, the polar deposits should be examined for microscopic evidence of biotic activity elsewhere on the planet.

Gaseous biomarkers

In addition to measurements in polar regions, collection of data on biogeochemically significant gases with landed detectors also capable of measuring wind direction and speed might also permit locating point sources of gas emanation, though this would probably be best done using a long-range rover. Molecular analysis of these gases would probably be best performed using compound-specific sensors, many of which are already available. Of course, stable isotopic analyses of these biogenic elements would also be desirable though more difficult to achieve.

Sample acquisition

In addition to the analytical experiments that can be deployed on the martian surface, it is important not to overlook the question of procedures whereby a series of martian samples can be delivered in suitable form to an analytical device. For specifically exobiological experiments, this aspect of surface science takes on particular importance because of the necessity of penetrating whatever barrier has permitted preservation of an organic record in an environment as generally hostile as that of the martian surface. Sampling procedures can be divided into four categories. The first, and simplest, is the scooping of a regolith sample and its delivery into a hopper, as was done on the Viking landers. The second type of sampling approach involves the removal of a coherent fragment from within a rock. This technology is not yet available for space-borne experiments, but would presumably involve coring or chipping by a device mounted on a rover arm.

The third type of sampling procedure is the retrieval of a subsurface sample from within the regolith. This is one of the most commonly considered approaches to evading the pervasive surface oxidant. We follow the example of most other workers in this area and identify a rotary drill-core as the logical approach to this problem, but other possibilities such as the use of penetrators should not be overlooked. The depth to which such sampling will be needed is not yet known; some workers believe that as much as ten meters may be necessary. Robotic drills with about one-meter capability were used on the lunar surface by the Russian Luna and Lunokhod spacecraft.

Finally, it may be necessary for some applications to consider the feasibility of performing certain specific operations, such as preparing a flat, or even polished, rock surface, or cutting a thin section of a rock. Suitable technologies for these requirements are not yet available for use on planetary spacecraft.

RETURNED SAMPLES

For many reasons it will be desirable, and probably necessary, for definitive experiments of exobiological significance to await return of appropriate martian samples for analysis in terrestrial laboratories. These should include a sample of pristine martian atmosphere in addition to lithic material, to permit more accurate chemical and isotopic analyses of gaseous species, particularly those present in only trace amounts.

Among the more important reasons cited for the importance of sample return are that many different methods can simultaneously be brought to bear in the analysis of one sample; that sophisticated instrumentation readily available in ground-based laboratories would be difficult (and expensive) to develop for use on Mars' surface; that, in any case, the latest and best techniques would be available in ground-based laboratories, as opposed to techniques that needed to be developed for spacecraft years before the instrumentation could actually be deployed; that conditions can be much more rigorously controlled; and that this approach allows for flexible responses to any surprising results that may arise during examination of the martian material.

Efforts to detect metabolic activities or to cultivate the organisms responsible for these activities would certainly be made, but specific approaches cannot be detailed without a knowledge of the specific features of sites from which samples were obtained. An important lesson from recent research in microbial ecology is that we have done rather poorly in cultivating terrestrial micro-organisms. Thus, it would be appropriate also to consider seriously various types of culture-independent analysis to characterize the extant martian biota. Other obvious issues related to conducting such analyses on returned samples include planetary protection and the potential for such organisms/activities to survive transit to Earth.

PLANNED MISSIONS: ANTICIPATED MEASUREMENTS AND OBSERVATIONS

This section is based on the mission scenario currently envisioned by the IMEWG. It is a plan for launching probes to Mars at every launch opportunity from 1996 to 2003. The plan assumes multiple launches, with the U.S. component being two launches at each opportunity so that failure or delay of one element will not result in a total failure for that opportunity. The plan also assumes that missions currently in their implementation phase will be launched as planned. The early missions are predominantly U.S. and Russian, so the scenario is strongly dependent on sustained funding for Mars exploration in both the U.S. and Russia.

THE 1996 OPPORTUNITY.

Three missions are approved for launch in 1996: the U.S. Mars Global Surveyor (MGS) and Pathfinder missions, and the Russian mission, Mars-96 (formerly Mars-94). The first of these is designed to recover part of the Mars Observer objectives.

Mars Global Surveyor

The U.S. MGS, the first element of the proposed multimission Mars Surveyor Program, is an orbital mission intended to recover part of the Mars Observer science objectives. However, the spacecraft, to be launched on a Delta, is considerably smaller than the Mars Observer spacecraft and the original payload cannot be fully accommodated. MGS will carry the following instruments of relevance to exobiology:

Camera. A camera incorporating both wide-angle and narrow-angle capability will provide planet-wide surface imagery and monitor global atmospheric and surface changes at 7.5 km resolution, partial coverage of the surface at a few tens of meters resolution, and selected targets at 1.4 m resolution. These cameras will provide some of the necessary information for geomorphology, geologic mapping (including establishment of relative chronologies), site selection and mission planning.

IR spectrometer. A thermal emission (mid-IR) spectrometer will map variations in the mineralogy of the surface and obtain temperature profiles of the atmosphere. This will permit identification of important surface lithologies of interest to exobiology, including evaporites and those characteristic of hydrothermal activity, mapping their global distribution at about 3 km spatial resolution.

Altimeter. A laser altimeter will determine surface topography. These data will permit definition of drainage divides and basins, necessary for evaluating the potential for aqueous sedimentary deposits. These data are also of crucial importance for planning of future landed missions, because topography places constraints on engineering and systems for landing.

Radio science. A multi-purpose radio-science experiment is expected to yield a greatly improved determination of the martian gravity field, needed for accurate interpretation of the altimeter data. It is also envisioned that the spacecraft would carry a communication antenna to relay back to Earth data from the Mars-96 penetrators and small landers (see below).

Pathfinder (Lander)

The U.S. Pathfinder mission will be launched on a Delta. It is primarily an engineering demonstration. Its main objectives are to develop and demonstrate a low-cost entry, descent and landing system that could be used for subsequent missions. It does, however, carry some instruments of scientific, and even exobiological, interest and will be landing in exobiologically interesting terrain. The primary landing site for Pathfinder is located on Chryse Planitia near the terminus of Ares Vallis (Latitude 20°N Longitude 34°W). The periodic and catastrophic outflows that created these channels could have transported detrital thermal-spring materials downstream from the thermokarst sources located in areas of chaos near their head reaches, depositing them at the lander site. This type of "grab bag" site has the advantage of providing access to a wide variety of lithologies from the surrounding regional geologic terrain, and in the case of Ares Vallis, may also provide samples of aqueous minerals that have a high priority for exopaleontology.

The instruments carried on Pathfinder include the following:

Camera. This will provide color stereo images of rocks near the lander, at about the same resolution as the Viking Lander cameras, but with 12 color filters for each camera rather than the 6 filters of Viking. These filters will permit a limited assessment of mineralogy, especially for iron oxides and pyroxene. In addition, there will be two filters for water-vapor detection and one for atmospheric dust.

Magnetic susceptibility experiment. In principle, this could supply some information about the mineralogy of the regolith close to the lander.

Pathfinder (Rover)

Mars Pathfinder will also carry a small, solar-powered rover that will be able to move within several to tens of meters from the lander, limited mainly by line-of-sight communications. The rover will carry the following instruments:

Camera. The camera used for navigation of the rover will also be used for scientific imaging. This will permit examination of local lithologies at a resolution of about 3 mm at 1 m range, giving some information about rock textures and fabric.

Alpha-proton-x-ray spectrometer (APX). This instrument can be placed in close contact with rocks and soils reachable by the rover, permitting analysis of the surface regions of those lithologies for the major rock-forming elements (O, Na, Mg, Al, Si, S, K, Ca, Ti and Fe) and carbon.

Mars-96 (Orbiter)

The Mars-96 spacecraft is to be launched on a Proton. It consists of an orbiter, two penetrators and two small landers. The penetrators and landers will be released to the surface shortly before the orbiter is injected into Mars orbit. The orbiter will carry a wide array of instruments of exobiological relevance:

Cameras. Three separate cameras are designed, respectively, for navigation, for low-resolution surface and atmospheric monitoring, and for high-resolution color and lower-resolution stereo surface mapping. As with Mars Global Surveyor, these images will provide basic information about martian geology, and will be invaluable for site selection and mission planning. Optimum spatial resolution will be ~10 m/pixel on the ground, with stereo "pixel height" resolution of ~20 m.

UV, visible and IR spectrometers. A variety of such instruments will provide information on the global distribution of major lithologic units, including aqueous mineral deposits. Spatial resolution of the visible and IR imaging spectrometer will be between 0.4 and 4.0 m/pixel over the spectral range 0.32 to 5.2 μm.

IR radiometer. The mapping radiometer will operate over a spectral range of 8.5 to 12 μm at 0.1 km/pixel and will map thermal anomalies at a resolution of 0.5 km/pixel.

Long-wave radar. This experiment will probe beneath the martian surface in a global search for subsurface water ice. It will operate with a range measurement uncertainty of 3.5 km.

Neutron and gamma-ray spectrometers. These instruments will map variations in the surface distribution of a number of key elements (H, C, Na, Mg, Al, Si, S, Cl, K, Ca, Ti, Fe, Th and U). Although the spatial resolution of this experiment is poor, essentially equal to the height of the spacecraft above the planet's surface, information on the global distribution of water is of fundamental importance to exobiology, as well as to many other disciplines. The data for the rock-forming elements will usefully complement the mineralogical mapping performed by the UV/Vis/IR spectrometers as well as being necessary for accurate derivation of water abundance from the spectrometer data.

Neutral mass spectrometer. This is designed to determine the elemental and isotopic composition of hydrogen, oxygen neon and argon in the upper atmosphere. These data, in conjunction with a variety of plasma experiments designed to characterize the solar wind and its interaction with the planet, will aid in reconstruction of the long-term evolution of the light-element inventories on Mars.

Mars-96 (Landers)

The objectives of the small landers are to determine the vertical structure of the atmosphere at the landing sites, to determine the chemistry of the materials at the sites, and to make prolonged magnetic, seismic, and meteorological measurements. To meet these objectives each lander carries a variety of instruments, of which the following will generate data of exobiological relevance:

Alpha-proton-x-ray (APX) spectrometer. Similarly to the case for the Mars Pathfinder rover, this instrument will yield the abundances of the rock-forming elements, and carbon, in the close vicinity of the lander. However, on Mars-96, resulting data will be mainly derived from regolith samples rather than from individual rocks.

Mars oxidant experiment (MOx). This experiment, which is being supplied by a US team, is designed to study the oxidant(s) apparently responsible for elimination of organic matter from the upper martian regolith. The MOx employs a series of fiber-optical detectors, coated with reagents sensitive to a wide range of different oxidants, which are exposed to the regolith close to the lander.

Mars-96 (Penetrators)

Each penetrator consists of two parts. A forebody will penetrate the surface to a depth of a few meters carrying with it several instruments of interest to exobiology:

Gamma-ray spectrometer. This will measure the concentrations of a number of elements (H, Na, Mg, Al, Si, K, Cl, Ca, Ti, Mn, Fe, Th and U) in the regolith within a meter or so of the penetrator.

Neutron spectrometer. This is designed to monitor the water content of the regolith within about 30 cm of the penetrator.

APX. This instrument will measure the composition of the regolith adjacent to the penetrator for the elements listed above for the lander APX.

The aft body, which remains at the surface, contains several instruments of which two are of particular exobiological relevance:

Camera. A camera operating in the visible range will image the terrain surrounding the impact site and local lithologies exposed at the surface near the penetrator.

Gamma-ray spectrometer. This will analyze the martian surface adjacent to the penetrator for the elements listed above in connection with the forebody instrument.

In conclusion, Mars-96 is a very comprehensive mission addressing a broad range of science questions, and making a variety of pilot measurements on the surface that will be useful for the design of subsequent more definitive experiments. It is also an international mission, the instruments being provided by a large number of nations.

THE 1998 OPPORTUNITY

Planet-B

In 1998 Japan plans to launch Planet B, its first nonlunar planetary mission. This will be a Mars mission launched on an M-5 rocket. The objectives of the mission are two-fold: (1) to study the martian upper atmosphere and its interaction with the solar wind, and (2) to develop technologies for future planetary missions. The scientific objectives are threefold. The first set of experiments will measure the structure, composition and dynamics of the ionosphere, the effects of interaction of the upper atmosphere with the solar wind, and the escape of atmospheric constituents. The second set of experiments will measure the intrinsic magnetic field, the penetration of the solar-wind magnetic field, and the structure of the magnetosphere. The third set of experiments will measure dust in the upper atmosphere and in orbit around Mars. Numerous instruments, which need not be detailed here, will be employed to perform this wide range of measurements, but of particular exobiological interest is a U.S.-supplied neutral mass spectrometer which will measure the elemental and isotopic composition of the upper martian atmosphere.

Mars Surveyor

The payload of this U.S. orbiter has yet to be determined but there is a strong desire for it to carry the two Mars Observer experiments not included on Global Surveyor:

Infrared radiometer (PMIRR). This instrument will map the three-dimensional structure of the martian atmosphere, including the distribution of water vapor, and will follow the transport of this water throughout the current martian system for a martian year. It has the capability to discover localized sources of water on the martian surface, if such exist.

Gamma-ray/Neutron spectrometer (GRS). As in the case of Mars-96, this instrument will map the chemistry of the surface, including the all-important distribution of near-surface hydrogen, *i.e.*, hydrated minerals or ice. The sensitivity of this spectrometer for near-surface water is likely to be somewhat greater than that of the Mars-96 instrument.

The orbiter will likely also carry a camera, an ultrastable oscillator and a relay antenna to service landers on the surface.

Current NASA plans call for launch of the 1998 Mars Surveyor orbiter on the proposed Med-Lite launch vehicle. The limited throw weight of this vehicle would probably restrict the payload to only one of the remaining Mars Observer instruments. If such an unfortunate circumstance transpires, exobiological priorities would strongly favor selection of the GRS.

Neolander

A Pathfinder-derived Mars lander is currently being considered by NASA for the 1998 opportunity. This "Neolander" would be sufficiently reduced in weight (175 kg landed mass vs. 270 kg for Pathfinder) so that it could be launched on a small launch vehicle, a Med-Lite instead of a Delta. The capabilities and instrumentation have yet to be defined, but the mission theme is planned to be Volatiles and Climatology, with emphasis on the history of water. This could result in measurement of light-element isotope ratios and volatile compounds in the regolith, both topics of significant exobiological interest.

Joint U.S.-Russian Activities

In addition to the above missions, the U.S. and Russian space agencies are exploring possible cooperative arrangements for Mars opportunities from 1998 on. Details of these activities remain to be defined at this time, but exobiology may well be one of the topics of Mars exploration of mutual interest to both parties.

THE 2001 OPPORTUNITY

The possibilities for 2001 are being evaluated. The U.S. Mars Surveyor program calls for at least two launches to Mars at every launch opportunity for the life of the program. The current plan is for the U.S. to use Med-Lite launches to place a network of small meteorological stations on the martian surface.

There is a similar uncertainty with respect to Russian plans. A Proton could be used to launch an as yet undetermined combination of previously developed vehicles.

THE 2003 OPPORTUNITY

2003 is the first opportunity at which an international network of multiple stations could be established on the martian surface. The ESA Intermarsnet concept would use an Ariane 5 booster to launch a Rosetta-derived carrier to Mars. The ESA carrier could deliver an ASI-furnished communications satellite into orbit around the planet and four landers built by an international consortium would be deployed on the surface. At the same time the Russians are exploring the possibility of using a Proton to send four Mars-96-derived small stations and two penetrators to the surface, and the U.S. could send two Mini-geolanders similar to those developed for the 2001 opportunity. Thus the possibility exists of having 12 simultaneously operating stations on the surface, thereby achieving the seismology and meteorology goals of a global network, and adding substantially to the number of sites at which we would have *in situ* measurements and observations.

A preliminary set of science goals has been established for the ESA-launched landers. The internal structure and dynamics of the planet will be determined by a network of simultaneously operating, broad-band seismo-meters, flux-gate magnetometers and transponders. The dynamics of the atmosphere and the atmospheric boundary layer will be studied using a network of simultaneously operating meteorology stations, and the vertical structure of the atmosphere at each landing site will be determined during descent. The geology and geochemistry of the landing sites will add further to our knowledge of Mars' diversity. All these objectives would be significantly enhanced if the ESA-launched probes were supplemented by or complemented by Russian- and/or U.S.-launched landers.

NECESSARY MEASUREMENTS/OBSERVATIONS MISSING FROM CURRENT PLANS

Current mission plans, either approved or proposed, of the U.S., Russia and Japan go a long way towards satisfying requirements for the early stages of the exobiological exploration of Mars. In particular, much of the global information required by exobiology will be met by existing mission plans, with two caveats. The first is that it is not yet certain that the GRS will be included in the 1998 orbiter. The second is that the present design of mid-IR spectrometer, TES, is restricted in its spatial resolution to about 3 km. This may well be inadequate for detection of outcroppings of aqueous mineral deposits by means of their characteristic mineralogy, a major goal in the survey phase of exobiological exploration. Also, there is currently no plan for instrumentation which could detect contemporary volcanic or hydrothermal activity, such as the release of characteristic gases (*e.g.*, H_2S, H_2, SO_x, HCl).

Among landed-science plans, there are more-conspicuous shortcomings from an exobiological perspective. Most serious of those, on a short to intermediate timescale, is the lack of a capability for either *in situ* mineralogical identification or the acquisition of subsurface samples from either regolith or rocks. Neither of these represents a uniquely exobiological requirement, in fact the former, and presumably the latter, would be of value to the broad Mars-science community. It is important to note that both of these capabilities will be needed early in the landed-science phase, to aid in planning of subsequent missions.

It is also notable that no specifically organic analysis is included in present mission plans. Ultimately, analytical instruments of considerable sophistication will be needed for characterization of any martian organics that may be present. However, before such narrowly focused experiments are deployed, we will need instrumentation capable of both identifying oxidant-free locations on the martian surface and then assaying them for the presence of organic matter. These capabilities will be needed on an intermediate timescale.

We conclude that current mission plans represent a generally sound basis for the progressive exploration of martian exobiology, but with a number of important exceptions. We identify the most immediate instrumentation needs as the following: Improvement in the spatial resolution of orbital mid-IR spectrometry; Design and construction of instrumentation for *in situ* mineralogical identification, description of the microenvironment (including oxidant distribution), and detection and characterization of organic matter; Development of a capability for acquiring samples from a depth of several meters in the regolith and from the interiors of rocks, and; Early deployment of the above.

Note that the above assessment is based on the assumption that all of the missions discussed earlier fly as planned. This may well be an overly optimistic assumption. In our opinion, the key experiments most vulnerable to programmatic changes are the orbital and landed gamma-ray spectrometers, and the EM sounders. If these fall victim to changes in the present plans, we urge their early incorporation into alternate missions.

SITE SELECTION

INTRODUCTION

Mars site selection, or knowing where to go on Mars to accomplish particular landed-science objectives, is fundamental for sound planning of future exploration efforts for exobiology. In the broadest sense, the search for martian life is guided by what we perceive to be the basic requirements for the existence of living systems, or for their preservation as fossils.

Site selection for Mars exobiology will be discussed in terms of the search for extant and fossil life. However, it should be noted that the same rationale that applies to the search for fossils on Mars, also holds for a prebiotic chemical record. On the Earth, this early precursor record has been lost, recycled by weathering and tectonics, and destroyed by emerging life. But such compounds are much more likely to have persisted within the more stable martian crust, particularly if life failed to emerge on Mars. In exploring Mars for precursor organic compounds, the most important targets are the same as those identified for fossil life, namely stable aqueous mineral deposits in ancient cratered terrains. Such deposits may have sequestered and preserved prebiotic organic molecules for several Gyr. Thus, even if martian life never developed, aqueous minerals, and especially the fluid inclusions they contain, remain as primary targets for exobiology.

The fundamental requirement for living systems is liquid water. Without it, metabolic activities of living cells would be impossible. Thus, to a large extent we equate the search for extinct or extant life with the search for liquid water, past or present. Given present martian surface conditions, stable, or nontransient, liquid water today can only be deep beneath the surface where higher temperatures and pressures favor its stability. But the deep subsurface of Mars is unlikely to be accessible for some time given the logistics and cost of "deep" (>few meters) drilling. Consequently, exobiological site selection is driven by the search for environments favorable either for the preservation of ancient life or for natural processes that bring extant subsurface life into surface environments.

HIGH RESOLUTION ORBITAL IMAGING

In planning for upcoming missions, the most pressing need is the selection and prioritization of targets for high-resolution orbital imaging. Terrestrial analog studies indicate that a resolution exceeding 30 m/pixel will be needed to resolve many important lower-order geomorphic features on Mars. Martian landforms visible at nominal Viking resolution (~200 m/pixel) are at a scale much larger than comparable features on Earth. To what extent this reflects major differences in process or small differences integrated over long time spans, is presently unknown. Thus, present site priorities are likely to need refinement as higher-resolution imaging becomes available for key sites and the criteria for geological processes and duration are reassessed.

Once exobiology sites have been imaged from orbit at high resolution, the goal is to search for appropriate aqueous mineral deposits using visible imaging to refine geological interpretations, and infrared and gamma-ray spectroscopy to interpret mineralogy. Such data will provide a basis for refining site priorities for future landed missions and for developing site-specific exploration strategies to explore for evidence of life. In developing exploration strategies for landed missions, it is important that we incorporate predictions from depositional facies models based on studies of terrestrial analogs, particularly during the early stages of exploration.

DURATION OF HYDROLOGICAL SYSTEMS

Prioritization of targets for orbital imaging is an important aspect of site selection because we will not be able to image all areas of interest at high resolution. In prioritizing sites for orbital imaging, emphasis is placed on geological features considered to be indicative of prolonged hydrological activity, as well as depositional processes that favor the long-term preservation of biological information. Table 1 provides an example of a comparative framework that emphasizes the level of integration of water-related geomorphic features within drainage basins as a basis for assessing the relative duration of hydrological systems in fluvial-lacustrine settings. We are presently limited in using this approach because we are not really sure how analogous martian landforms are to those on Earth. In part this stems from a general lack of high-resolution imaging at critical sites and an inability to resolve many smaller-scale landforms that may be critical to interpretations of process and duration. As higher-resolution imaging (<30 m/pixel) becomes available, it is important that we carry out comparative geologic studies of key sites to evaluate relative duration. Of course, our estimates of duration based on comparative geomorphology will eventually need to be calibrated to absolute time scales based on radiometric dating of martian samples.

HIGH-PRIORITY SITES FOR EXTINCT MARTIAN LIFE

In selecting sites for exopaleontology (*i.e.*, the search for fossils or biomarkers), priority is given to landing sites in ancient terrains where hydrological systems involving liquid water appear to have been long-lived and which exhibit a high probability of having surficial aqueous mineral deposits. We also give preference to mineral deposits that are likely to have had a long residence time in the martian crust, namely, those that are diagenetically stable and resistant to chemical weathering. Examples include silica (as chert) and apatite (as phosphate). It should be noted that fine-grained detrital sediments also provide a suitable host for fossils and organic matter. Especially favored are clay-rich sedimentary deposits formed in environments that were reducing, with rapid sedimentation and compaction, and where permeability was further minimized by early cementation. Given the absence of plate tectonics on Mars and the attenuated hydrological cycle there, ancient terrains (>3.0 Gyr) are probably much more widespread and better preserved than on Earth.

In exploring for evidence of an ancient biosphere, site selection is guided by what we have learned about fossilization processes through studies of ancient (Precambrian) rocks on Earth, and studies of terrestrial environments regarded to be good analogs for the early Earth and Mars. Because the development of a martian biosphere in surface environments is likely to have been interrupted very early (~3.0 Gyr), we believe the microbial record of the Precambrian provides a reasonable proxy for Mars, allowing for obvious differences in geological history and environment.

The Precambrian terrestrial record reveals that the long-term preservation of microbial fossils requires rapid entombment of organisms by fine-

TABLE 1. Geomorphic Criteria for Evaluating the Duration of Fluvial-Lacustrine Environments on Mars

FEATURES	DURATION	
	SHORTER	*LONGER*
Channels:	Straight	Meandering
Floodplains:	Absent	Broad
Drainage Network:	Simple	Dendritic
Drainage Basins:	Small Many divides	Large Few divides
Tributaries:	None to first order	Second or higher order
Stream Terraces:	Single level	Multiple level Incised meanders
Deltas:	Absent or small	Large, multi-lobed
Other:	Only young craters present	Craters show varying degrees of erosion

grained aqueous mineral phases that are stable and which retain biological information through diagenesis. In many Precambrian examples, mineralization occurred very rapidly, prior to cellular decomposition, and probably while organisms were still viable. The best preservation is observed where organic materials were rapidly perfused with fine-grained silica or phosphate.

Other potential host minerals include carbonates, which are less stable, but which also have long crustal residence times. Evaporites, which comprise another group of potential host minerals, are quite soluble and tend to dissolve in an active hydrologic cycle. But the crustal residence times of aqueous minerals on Mars are likely to be longer due to the dry climate and the absence of tectonic overprinting. Thus, while Precambrian evaporites are rare on Earth, they may be abundant on Mars where evidence suggests that the hydrologic cycle was interrupted early. As noted previously, environments that are especially favorable for microbial fossilization include mineralizing subaerial and subaqueous springs, evaporites, and certain hard-pan soils.

Thermal-Spring Deposits

Subaerial thermal-spring deposits are regarded as excellent targets in the search for a fossil record on Mars because of the high biological productivity and pervasive early mineralization typically associated with such systems. Volcanic terrains are widespread on Mars and some possess outflow channels that are likely to have formed by spring sapping. The association of such features with potential subsurface heat sources, such as volcanic constructs or thermokarst features, indicates the possibility for past hydrothermal activity on Mars. Thermokarst features and related chaotic terrains that may have been formed by hydrothermal processes are also prime targets for hydrothermal mineralization and a fossil record. For example, many of the outflow channels comprising Simud, Ares and Tiu Valles systems originate from chaotic terrains of probable thermokarst origin, or from the floors of chasmata related to the vast Vallis Marineris system (*e.g.* Echus Chasma). Target deposits here include the common thermal-spring minerals, silica, carbonate, and iron oxides, as well as clay-rich hydrothermal alteration halos associated with shallow igneous intrusives.

Dao Vallis-Hadriaca Patera (Latitude: 33.2°S, Longitude: 266.4°W)

This is a broad outflow channel of simple form that originates from an amphitheater-shaped source area on the southern flank of Hadriaca Patera, an ancient highland volcano. The outflow channel is believed to have formed where a localized subsurface heat source melted ground ice. This process is likely to have been associated with sustained hydrothermal activity. The process probably created not only Dao Vallis but similar outflow channels to the south (*e.g.*, Harmakhis Vallis). The large size of the outflow channel suggests that the interval of activity may have been sustained long enough for extensive hydrothermal mineralization, favorable for the preservation of fossils and organic chemical fossils.

Dao Vallis clearly meets several important criteria as a site for exopaleontology and will be a recommended target for high-resolution visible imaging during upcoming missions. Such information is needed to evaluate fully the origin of important small-scale features (such as the knobby terrain on the floor of Dao Vallis, potential spring mounds) and shed light on both the nature of hydrological processes and their duration. But to assess accurately the potential of this site for exopaleontology, high-resolution infrared spectral data are also needed to explore for hydrothermal mineral deposits, such as silica, travertine, or iron-oxide sinters.

Spring outflows may have also transported thermal-spring minerals to the channeled plains of the Hellas Basin, a potential site for landed missions, and also to the Pathfinder landing site in Ares Vallis.

Sublacustrine Spring Deposits and Carbonate Cements

In arid lake basins on Earth, coarse-grained, nearshore facies are often a locus for extensive carbonate mineralization. This process is of particular interest to exopaleontologists because such mineralization typically enhances the preservation of both microbial fossils and organic matter. For example, in many alkaline lakes in the Great Basin (western United States), micro-organisms living on the surfaces of submerged tufa mounds associated with subaqueous springs, or living interstitially within coarser sediments of lake-margin facies (*e.g.*, fan delta deposits), are commonly entombed by precipitating carbonate minerals. In ancient tufas, evidence of microbial activity is preserved as cellular microfossils and stromatolites, as well as disseminated organic matter. Such deposits are regarded as excellent targets in the search for a fossil record on Mars.

Margaritifer Sinus-Parana Vallis (Latitude: 22°S, Longitude: 11°W)

This site is located within an ancient cratered terrain that has been heavily dissected by several major dendritic valley networks. Channel networks surround a central basin that may have been a depocenter for fluvial-lacustrine sedimentation. Most of the valleys debouch along the southeast margin of the basin. In general, basin-floor sediments appear to be exposed at the surface, although in places hummocky features may be an aeolian mantle.

Formation of the valley networks surrounding the basin was apparently preceded by an early period of mostly larger impacts, evidenced by dissection of the rims of many of the older craters by headward erosion of the channels. The period of hydrologic activity that produced the valleys was followed by a period of smaller impacts, some of which were superimposed on the older craters and valleys. That the intervening period of hydrologic activity that created the valleys may have been of relatively long duration is indicated by the presence of two or more levels of tributaries in several of the longer channel systems and varying degrees of channeling on the rims of the older craters.

Gusev Crater (Latitude: 15.5°S, Longitude: 184.5°W)

A second high-priority fluvial-lacustrine site is Gusev Crater, an impact basin of ~135 km diameter that is located in ancient cratered terrain. The system consists of a single, ~800 km long channel (Ma'adim Vallis) that flowed north, debouching along the southern margin of Gusev Crater. Several different levels of stream terracing, present within the steep-walled canyon, likely record rapid changes in base level. In addition, the lower end of the valley is deeply incised by a much smaller channel that formed by headward erosion late in the history of Ma'adim. Base level changes could have been controlled by drops in the level of a paleolake that resided within the Gusev Crater, or perhaps by local tectonic uplift. These observations support a prolonged hydrologic history for the Ma'adim-Gusev system, although distinction of the processes responsible for the observed changes in base level will require higher spatial resolution than is presently available from Viking.

Just basinward of the terminus of Ma'adim Vallis are lobate deposits that were channeled by late-stage downcutting of outflows from Ma'adim Vallis and subsequently wind eroded. Terracing above and below these deposits suggest they are fluvial-deltaic in origin. The depositional units of the delta are deeply channeled, and stand in high relief above the surrounding crater floor, suggesting they are well indurated. Deltaic and marginal lacustrine deposits are commonly a locus for precipitation of carbonate cements and sublacustrine spring tufas, processes that favor the preservation of fossils and organic matter. In addition, coarser-grained channel deposits may contain fossiliferous clasts derived from older formations upstream. Ma'adim Vallis originates within an extensive chaotic terrain to the south that appears to have formed by thermokarst processes. Thus, throughout its long history, hydrothermal minerals may have been carried to the floor of Gusev Crater from the source areas of Ma'adim Vallis. Refinement and testing of this scenario will require high-resolution visible-range imaging, and infrared spectral data to assist in the search for carbonates or other aqueous minerals.

Evaporites and Lacustrine Shales

Terminal lake basins in arid environments on Earth are usually ephemeral in nature and eventually dry up, depositing their dissolved salts while forming flat playa basins. Evaporite minerals formed in such environments frequently incorporate micro-organisms within fluid inclusions during crystallization. Such deposits have been suggested as potential short-term repositories for viable organisms, or longer-term repositories for cellular fossils and biomolecules. In addition, the fine-grained, clay-rich shales often interbedded with evaporites in these settings provide good repositories for organic matter, particularly where early cementation occurs. Given the numerous paleolake basins that have been identified in ancient terrains on Mars, such deposits hold much interest for exopaleontology.

White Rock (Latitude: 8°S;Longitude: 335°W)

High-priority targets on Mars for evaporites include an unnamed 80-km crater within the Sinus Sabeaus Quadrangle. Numerous channels resembling terrestrial dendritic drainage systems surround the crater basin and may have sustained a paleolake for some undetermined interval of time. The crater floor exhibits patchy albedo of varying intensity. Of particular interest is a spindle-shaped mound of relatively high albedo called "White Rock". This feature exhibits two sets of irregular, wind-eroded fractures and is similar in form to terrestrial yardangs. It has been suggested that White Rock is a playa deposit consisting of chemically precipitated evaporite minerals. This interpretation implies that a hydrological system operated here for a long period of time, first concentrating soluble salts by chemical dissolution and then removing them by evaporation and precipitation. Similar high-albedo features can be found on the floors of other impact craters on Mars (*e.g.*, crater Becquerel, Latitude: 21.3°N; Longitude: 8°W), some showing irregular stratification under high resolution. This suggests that martian evaporites may be fairly widespread.

HIGH-PRIORITY SITES FOR EXTANT LIFE

As mentioned previously, if life exists on Mars today, it is likely to be a chemosynthetic form residing in subsurface habitats where liquid water may be present. Despite the inaccessibility of the deep subsurface during upcoming missions, it is possible that recent outflows of subsurface water have brought such organisms into near-surface environments where they may have been cryopreserved in ground ice. Thus, areas of stable ground ice associated with very recent outflow channels are probably our best hope for discovering extant life. It has been argued, both on empirical grounds as well as theoretical evidence, that ground ice is presently unstable on Mars at latitudes <40°. Therefore, as noted previously, exploration for cryopreserved martian life should be focused at higher latitudes.

In prioritizing sites for extant life, we should emphasize the very youngest martian terrains (*e.g.*, preferably those completely lacking impact craters). It has been suggested that micro-organisms may survive in ground ice for possibly millions of years and in evaporite deposits for perhaps hundreds of millions of years. Such suggestions should not be ruled out, despite the likelihood that the normal background radiation in such deposits, integrated over geologic time, may severely restrict long-term organism viability by destroying (*via* mutagenesis) the genomic integrity of cells. The survival time of dormant, but viable organisms under martian conditions is poorly constrained at present, as are the factors that affect preservation during the transition to the fossil record.

In searching for extant life, present knowledge suggests that we should focus on high latitudes (>40°) where stable ground ice may be present, and especially at sites where ground ice may have formed in association with recent outflows of subsurface aquifers. It follows that mapping the distribution of ground ice using gamma-ray spectroscopy has a high priority for exobiology. It is also possible that surface life may survive within undiscovered liquid water refugia near the surface (*e.g.*, shallow hydrothermal systems), although such environments, if they exist, may be very difficult to locate. It is possible they could be identified using thermal IR. Areas of persistent fogs and frosts at the martian surface, noted previously, may provide indications of near-surface water or water ice that could be accessed by shallow drilling.

Ground ice appears to provide an excellent medium for preserving organisms and biomolecules, but only for short intervals of geological history (perhaps hundreds of thousands to possibly millions of years). Ice may inhibit oxidation of the soil and slow the breakdown of organic materials. But global climate changes, driven by obliquity or other orbital variations, have left the Earth completely ice free on numerous occasions in its history. The present ice caps probably formed during the Miocene and have waxed and waned irregularly since then. The same variations are likely to be true for Mars. Thus, while knowing the present distribution of ground ice on Mars is basic to a strategy to search for extant life there, finding stable ice that is likely to have formed in association with recent outflows of subsurface water, or water-rich pyroclastics, such as lahars, provides the most logical approach.

Ismenius Lacus (Latitude, 44°N; Longitude, 333°W)

Several high-priority targets for cryopreserved organic materials have been located within the Ismenius Lacus Quadrangle of Mars . This terrain lies within the Amazonian-aged "hilly unit" of Deuteronilus Mensae. This area is dominated by numerous mesa-like landforms which are surrounded by debris aprons that resemble terrestrial rock glaciers. The "softening" of mesa rims and associated

Debris aprons surrounding steep-sided mesas, Deuteronilus Mensae region (Ismenius Lacus Quadrangle) of Mars. At a latitude of nearly 45° North, ground ice could be present in this area of Mars, contributing to the movement of material downslope as rock glaciers.

features suggest the activity of near-surface ground-ice. Mid-winter ice is thought to precipitate from the atmosphere and mix with rock and soil to form masses that slowly creep downslope under the influence of gravity (rock glaciers). The latitude of the area, in combination with the various geomorphic features discussed above, indicate that near-surface ground ice, though varying seasonally, has probably been present here for some time. But the proposed periglacial origin of this terrain needs to be evaluated in more detail using gamma-ray spectroscopy to confirm the presence of ground ice. Unfortunately, young outflow channels that may have delivered a subsurface biota to the ground-ice environment remain to be discovered.

North Polar Cap

Important potential targets for indirect evidence of extant life are the polar regions, with their ice caps and layered terrain. Molecular, and even morphologic, signatures for life could have found their way into polar ices which probably act as cold traps for organic molecules in the atmosphere. This has the added advantage that we already know where polar ice is located. A landed mission to the water-rich north polar cap, likely to be targetted primarily at climatological goals, could also be of considerable exobiological value, provided that it combined capabilities for subsurface drilling with *in situ* organic analysis and microscopic examination of fine particulates.

PLANETARY PROTECTION FOR MARS MISSIONS

NASA's planetary protection policy and its implementation demonstrate to the public that NASA is safeguarding the planets, including our own, during space exploration. The U.S. is signatory to a 1967 international agreement, monitored by COSPAR, which establishes the requirement to avoid forward and back contamination of planetary bodies during exploration. To help implement requirements, NASA established a Planetary Protection Office and has issued a document, NHB 8020.12, that delineates planetary-protection requirements for all NASA robotic extraterrestrial missions. This document is specifically directed to: 1) the control of terrestrial microbial contamination associated with robotic space vehicles intended to land, orbit, flyby, or otherwise be in the vicinity of extraterrestrial solar-system bodies, and 2) the control of contamination of the Earth and Moon by extraterrestrial solar-system material collected and returned by such missions.

The increasing interest in Mars exploration and the long time elapsed since consideration of the scientific rationale for such exploration, have prompted a new look at the planetary protection requirements for forward contamination. In 1992, the Space Studies Board of the U.S. National Academy of Sciences recommended changes in the requirements for Mars landers that significantly alleviated the burden of planetary protection implementation for these missions. The recommendations were published in "Biological Contamination of Mars: Issues and Recommendations" and presented at the 1992 29th COSPAR Assembly in Washington DC. In 1994, a resolution addressing these recom-mendations was adopted by COSPAR at the 30th Assembly and has been incorporated into NASA's planetary protection policy. As we learn more about Mars, the requirements may change again to reflect current scientific knowledge.

The academy's recommendations, subsequently adopted by COSPAR, recognize the very low probability of growth of micro-organisms on the martian surface. With this in mind, the policy shifts from probability of growth considerations to a more direct and determinable assessment of the number of micro-organisms with any landing event. For landers that do not have life-detection instrumentation, the level of biological cleanliness required is that of Viking prior to heat sterilization, which can be accomplished by class 100,000 clean-room assembly and component cleaning. This is a conservative approach that minimizes the chance of compromising future exploration. Landers with life detection would be required to meet Viking post-sterilization levels or levels dictated by the experiment. It is recognized that the sensitivity of a "life-detection" instrument may impose the more severe constraint on the mission.

Included in the changes to the COSPAR policy is the option that an orbiter is not required to remain in orbit for an extended time if it can meet the standards of a lander without life-detection experiments. Also, the probability of inadvertent early entry has been relaxed compared to previous requirements.

The policy for samples returned to Earth is directed toward containing potentially hazardous martian material. Concerns have included a difficult-to-control pathogen capable of directly infecting human hosts (extremely unlikely) or of a life form capable of upsetting the current natural balance of Earth's ecosystem. It is of paramount importance to address the potential public perception that might attribute an epidemic, personal illness, or unusual event to an introduced martian contaminant.

For a Mars sample return mission, all samples would be enclosed in a hermetically sealed container; the contact chain between the return vehicle and the Mars surface must be broken in order to prevent the transfer of uncontaminated surface material *via* the spacecraft exterior; and the sample would be subjected to a comprehensive quarantine protocol to investigate whether or not harmful constituents are present. It should be noted that even if the sample return mission has no exobiological goals, the mission would still be required to meet the planetary protection sample return procedures and the life-detection protocols for forward contamination, not only to mitigate concern of potential contamination but also to prevent a hardy terrestrial hitchhiker from masquerading as a martian life form. In today's environment, public concern and legal requirements (in multiple jurisdictions) would be significant drivers in mission planning and planetary protection implementation. It may be worthwhile to consider maximizing those experiments that could be done on the martian surface, thereby extending the time before a sample return and perhaps relaxing fears of back contamination, leading to delayed, and possibly reduced, cost.

Because of the high level of public concern over the possibility that a sample returned from Mars might contain components harmful to our health or to the Earth's biosphere, NASA must strive for public education as well as informed public and legal consent well in advance of a sample return mission. In part, the planetary protection office provides a visible regulatory function which might mitigate concerns of forward and back contamination.

RECOMMENDATIONS

SUPPORT OF BASIC R & A

Only with spacecraft missions will we be able to answer such questions as the extent to which prebiotic chemical evolution took place on Mars, whether life ever originated on Mars, or whether life exists on Mars today. However, the intelligent pursuit of those issues also involves a significant level of ground-based activity that falls under the general heading of basic research and analysis. These activities help to improve our ability to obtain and interpret data from Mars missions, and they help in formulating more effective strategies for conducting future exobiological exploration. The definition of flight instrumentation also falls under this activity but is best discussed in the context of instrument development in the following section.

Analyses of Mars-analog and Martian Materials

Our ability to interpret data and to design future experiments depends strongly upon our understanding of the composition of Martian materials. One useful approach is to propose candidate samples, *e.g.*, rocks or soils, whose properties are broadly consistent with those previously observed *via* telescopes, the Viking mission and martian (SNC) meteorites. These model materials can then be tested and modified as additional observations become available.

For example, the Viking biology experiments revealed that the martian soil was chemically very reactive in ways that were unanticipated. Earth-based laboratories have attempted to reproduce the performance of the biology experiments using materials which conform to the constraints imposed by all Viking analytical experiments. This effort has helped to restrict the number of geochemical agents, some of which are powerful oxidants, with properties consistent with the Viking observations. These studies have led to the development of the MOx "oxidant experiment" for the Russian Mars '96 mission, which is designed to identify these chemical agents more conclusively.

Much of our current detailed understanding of martian geochemistry stems from studies of martian meteorites (*i.e.*, the SNC meteorites) in earth-based laboratories, recognizing that they represent a very incomplete sampling of martian lithologies. Conspicuous examples of such insights include: the entirety of our radiochronometric knowledge of the timing of igneous activity and much of what we know about the magnetic properties of martian rocks; virtually all of our observations of martian igneous petrology; our understanding of crustal and mantle differentiation processes as inferred from the distributions of elements (major, minor and trace) among different lithologies; and most of our knowledge of stable-isotope distributions among the various reservoirs, with important implications for the evolution of the martian atmosphere and hydrosphere.

Analyses of martian meteorites will continue to play a key role, even as additional *in situ* spacecraft measurements are made and martian samples are returned to Earth; such meteorites broaden the diversity of materials available. Thus, continued support of martian-meteorite research is an important element of exobiology strategy. Support should continue for analyses of those meteorite components relevant to exobiology, improvements in relevant laboratory instrumentation, and field collection of meteorites in Antarctica. The Antarctic program has yielded several key SNC meteorites.

Biogeochemistry and paleontology of Mars-like environments

Because certain field sites on Earth serve as useful proxies for martian environments, these sites can prepare us for the challenges of Mars exploration. Such localities include the dry valleys and lakes of Antarctica, boulder fields and ephemeral lakes in deserts, and hydrothermal systems and thermal springs. All of these environments harbor ecosystems living under harsh conditions; and their study can guide our search for an extinct or extant martian biosphere. A key concern is the fossilization processes and potential in different environmental settings. We must rigorously define the true limits to life as we know it, and we must compare these limits with the full range of environments available on Mars, including those deep beneath its surface. We must learn how to recognize all evidence of martian life and its fossils, yet we must acknowledge that this evidence probably will differ in fundamental ways from the evidence we already have obtained about our own ancient biosphere. Still, basic paleontological principles and knowledge of preservation processes in extreme environments provide the basis for a strategy to explore for martian fossils. Such studies will therefore continue to be important as future Mars observations increase in their variety and sophistication.

Interdisciplinary studies

In addition to the focused research on specific aspects of the martian environment described above, a key element in developing our understanding of the planet Mars involves the integration of new results into a coherent view that is consistent with the full range of martian studies. Such an interdisciplinary approach draws from exobiological, geochemical, geological and atmospheric studies in order to understand the system as a whole. Each of these disciplines provides a different set of constraints on the nature of the system, and the system as a whole must be consistent with each of the component parts. In this sense, the field of exobiology encompasses all of the other fields to the extent that each contributes to our understanding of the requirements of, and constraints on, the origin, evolution and distribution of life. This interdisciplinary approach also includes analysis of existing data that might pertain to exobiology even if those data were obtained in pursuit of other planetary-science goals.

Definition of science goals

Finally, one of the most important roles of basic R & A in any planetary-science discipline, including exobiology, is to help formulate the science goals for future planetary missions. Thus, this strategy document not only builds upon the record delivered by the Viking missions, but also reflects advances in a wide variety of areas that are not immediately mission-related, notably basic research into such topics as Precambrian paleontology, microbial ecology, impact theory, evolution of planetary atmospheres, remote-sensing instrumentation, and many others. It will remain essential to the future of planetary exploration, in general, and exobiological exploration, in particular, for translation of basic discoveries into mission objectives to continue to receive recognition and support.

INSTRUMENT DEVELOPMENT

To reiterate a point made previously, specific instruments mentioned here should be regarded as examples and should not be interpreted as excluding definition and development of new concepts, particularly insofar as such novel technologies might permit reduction in either weight or cost.

Orbital instruments

As discussed earlier, two of the key aspects of global investigations in support of exobiology are the searches for water and aqueous mineral deposits, respectively. For water, the technique of choice for global searches is gamma-ray/neutron spectroscopy. This represents quite a mature technology but some significant improvements are worth considering. Because of their sensitivity to background radiation generated by the spacecraft structure, existing spectrometers need to be deployed on a boom that adds both weight and complexity to the system. By taking advantage of two recent developments, however, the need for a boom disappears. First, by replacing much of the aluminum in the spacecraft structure with carbon-based composites, the background radiation level can be greatly diminished. Second, by employing anti-coincidence shielding around the detector, the remaining background can be effectively eliminated. However, use of anti-coincidence shielding requires adoption of active mechanical cooling, rather than passive cooling by radiation to space, as at present. This in turn carries a weight penalty, but this weight increase is offset by elimination of the boom.

The search for hydrothermal and other aqueous mineral deposits is currently hampered, as noted earlier, by the spatial resolution of the present generation of orbital mid-IR spectrometers. At a value of about 3 km/pixel, this is a factor of about 30 too large for reliable deconvolution of spectral signatures for discrete outcrops of aqueous minerals or mounded spring deposits. (A resolution of 30 m would probably be an appropriate goal.) There seems to be no obvious physical impediment to an improvement of about that magnitude in the spatial resolution of such a spectrometer, a development that would be most desirable. It is worth noting that such detailed mineralogical information would be of value not only to the exobiological community but also to geochemists and those working on the geological and atmospheric evolution of Mars.

Landed instruments

From an exobiological perspective, the need among landed instrumentation is not so much in improvement of existing analytical instruments as in development of new technologies. However, one area in which improvement is certainly needed is the *in situ* identification of surface mineralogy. Two approaches are feasible here and, because they yield data in somewhat different situations, both should be developed.

The near- and mid-IR spectroscopic techniques employed from orbit for mineral identification, can also be applied on a smaller scale to yield information on the minerals exposed at the surface of a rock within the field of view of a landed spacecraft or rover. Thus, this would be a powerful technique for conducting an assessment of the mineralogical diversity at a landing site, a key tactical goal of exobiological exploration.

The survey mode of IR spectroscopy would be usefully complemented by the use of x-ray diffraction applied to individual rocks selected on the basis of IR data. Because of the unique crystallographic signature that x-ray diffraction yields for most minerals, this is a very effective means of defining martian surface lithologies, which can be made even more useful by combining it with x-ray fluorescence spectroscopy, thereby yielding elemental abundances in addition to mineral identities. Again, the acquisition of detailed mineralogical information has an importance in Mars exploration that far transcends a single discipline, such as exobiology, so that development of miniaturized IR spectrometry and combined x-ray diffraction/fluorescence would be of major benefit to Mars science.

Several analytical approaches of exobiological relevance are, however, missing from the current roster of planned experiments on the martian surface. Most conspicuous among these is the capability for molecular and/or isotopic analysis of volatile, particularly organic, species. We therefore recommend development, and eventual deployment, of the following types of instrument: Evolved-Gas Analyzer, combined with either a Differential Scanning Calorimeter or Differential Thermal Analysis; either an Isotope-Ratio Gas Mass Spectrometer or a Tunable Diode Laser Spectrometer for isotope analysis; and, possibly instruments designed for various specific classes of organic compounds, such as lipids and amino acids. In view of the need for considerably more information about the martian micro-environment before deployment of such specialized sensors for analysis of possible organic compounds, it seems unlikely that these instruments would be needed before the 2001 flight opportunity, but it would be most desirable to have them available for inclusion soon thereafter. (However, the first two types of instrument could be usefully employed on inorganic materials, such as evaporite deposits or hydrothermal alteration products, with significantly less prior investigation.)

Also missing from current plans, except for inclusion of gamma-ray spectrometers on the Mars-96 penetrators and the long-wave radar on the Mars-96 orbiter, are the means for mapping the subsurface distribution of water. Development and early deployment of EM sounding would therefore be highly desirable.

MOBILITY AND SAMPLE ACQUISITION

Optimization of the science return from instruments landed on the martian surface will require both that the instrument be in the right location to acquire the desired data and that, for cases in which analysis is performed on a discrete sample of martian material, that the sample be brought to the instrument in an appropriate form. Thus, successful Mars science places a premium on both mobility and sample acquisition.

Mobility

Considerable thought has already been invested in devising ingenious methods of moving instrument packages on Mars from their landing site, which is likely to be, at least for early missions, in geologically bland terrain, to a location of more geological, geochemical, geophysical or exobiological interest. Rovers, balloons, hoppers and aircraft have all been proposed, with both the U.S. and Russia having designed rovers for use in Mars exploration. These two rovers represent two very different concepts, the U.S. Pathfinder microrover being an extremely small, sophisticated device with limited science capability, whereas the Russian Marsokhod is much larger with a capability of carrying a diverse scientific payload. Both approaches have their merits, but we note that, if the telecommunications link between the rover and ground passes through the lander, the rover's range is limited to line of sight, so that the larger the rover, the greater its range. Furthermore, only a large rover will provide a suitable platform for drills capable of penetrating into rocks and the subsurface regolith. Given the likely exobiological importance of such a drill-core, we therefore recommend development of a suitably large rover.

A key aspect of rover design will be navigation and control. Recent developments in telepresence and virtual reality have already shown great promise in this area and we recommend continued support of work in this field.

Sample acquisition

Approaches to sample acquisition run the conceptual gamut from a simple scoop and hopper arrangement to an automated thin-section maker for rock samples. As noted earlier, exobiology places particular demands on sample acquisition because of the common need to retrieve samples from locations shielded in some way from the local martian environment. Thus, acquiring samples both from beneath the surface of the regolith and from the interior of weathered sedimentary rocks is likely to be necessary at some stage in Mars exploration.

The need for a drill, or some equivalent means of accessing the subsurface regolith, has been apparent for some time and several concepts have been considered. One of the major unknowns at this time is the depth to which such a drill will need to penetrate. This is largely governed by the depth distribution of the surface oxidant, about which nothing is presently known except that it exceeds the depth from which the Viking Lander obtained a trench sample for the Life Detection Experiments, namely about 10 cm. The consensus is that a depth of several meters is worth striving for, with a minimum target depth of 1 m. We therefore recommend that development proceed on a coring drill capable of penetrating to a target depth of 3 m into the martian regolith.

The need for a technique capable of extracting a sample from the interior of a rock has also attracted attention, though less effort has been put into this area. Nonetheless, in view of the importance of removing the influence of martian weathering from rock analyses, and the key role that fluid inclusions and other entombed volatiles can play in geochemistry and climate research, as well as in exobiology, we recommend development of techniques that will permit access to the interior of rocks lying on the martian surface.

MISSION PLANNING

Orbital missions

Assuming that currently approved missions perform as planned, and that a gamma-ray spectrometer is included in the '98 Mars Surveyor mission, the only presently identifiable exobiological goal requiring an orbital mission would be the identification of surface expressions of aqueous mineralization, such as hydrothermal systems or spring deposits, for which high-resolution imaging of selected sites by means of mid-IR mapping spectrometry would be needed. Current plans do not include any approved or proposed missions for which this would be a straightforward opportunity, although the Termoscan instrument on the Mars 96 mission, with a spatial resolution of 0.5 km/pixel, may come close to achieving this goal. Otherwise, the earliest plausible launch opportunity for such an experiment may well be 2003.

Landed missions

Unlike the case for orbital missions, current plans include several proposed landers for which the scientific payloads are undefined at this time so that, in principle, exobiologically oriented instruments could be included. The problems in this case are threefold. First, each lander is likely to have an extremely low payload mass, severely limiting the range of experiments that may be included in each one. Second, the competition among different Mars-oriented disciplines for inclusion of instruments on each lander will be fierce. Finally, optimization of exobiological goals will put a premium on landed missions to visit a diverse range of sites, which translates into a requirement for inclusion of exobiological experiments on several different landed missions.

Nonetheless, we recommend establish-ment of a sequence of landed missions, beginning with development of a geochemically oriented payload capable of regional chemical and mineralogical analyses, oxidant identification, and volatile-element detection. This payload would be dispatched to a geologically diverse range of sites (see following section on site selection), which would be identified by means of high-resolution orbital data. This series of landed missions would lead in turn to identification of a limited number of sites of well-defined exobiological interest, to which would then be dispatched a more exobiologically focused payload incorporating molecular and isotopic analysis of crustal volatiles. This phase of exploration would also involve high-resolution local imagery aimed at assessing local lithologies for their potential to preserve fossils or to harbor extant life.

Positive results for either preserved organic matter, potentially fossiliferous rocks, or habitats suggestive of extant life would then require deployment of highly focused experiments designed to test for modes of prebiotic chemistry, the presence of fossils, or evidence for metabolic activity, respectively.

It is our view that landed missions should possess the mobility necessary to generate regional, rather than purely local data. Such mobility will allow access to sites that may be virtually unreachable by fixed landers for landing safety considerations. For example, if a hydrothermal area has been located using high-resolution orbital imaging it may well be the case that the nearest terrain suitable for landing is several 10s of km away. Another advantage of mobility is that it exploits the natural variability of Mars. For example, when drilling in search of unoxidized materials, in many locations the depth of the oxidation zone may exceed the depth of the drill. A rover can move along geological or topographic boundaries until a location with a shallower layer of oxidizing material is found. Direct bedrock outcrops could also possibly be studied this way.

Sample return

Many of the techniques in geochemistry and paleontology that are used in exobiology-related studies on Earth do not lend themselves to field applications. Of particular relevance here is the difficulty that may be anticipated in conclusively identifying fossils of past life on Mars without returning a sample. Furthermore, any positive signal from a robotic life-detection experiment would obviously demand confirmation in a terrestrial laboratory. For these reasons, we recommend sample return as a key part of the long-range exobiology mission strategy. Clearly, a sample return would follow after a series of surface lander and rover missions had analyzed samples from sites that had been identified as of particular interest.

Human exploration

Exobiology, in particular the search for extant and fossil ecosystems, is one of the few planetary science areas that may require human presence. The importance of field work in ecology and paleontology is well understood. Not all the tools for conducting field work robotically on another planet have yet been developed or proven. We strongly urge continuing development of such robotic techniques but recognize that it may be the case that a successful prosecution of the search for life-forms on Mars will ultimately require the active participation of life-forms from Earth.

SITE SELECTION

A site-selection strategy to explore for martian life must proceed from first principles derived from studies of Precambrian paleontology and modern terrestrial analogs. The exploration for an ancient martian biosphere should emphasize the search for aqueous mineral deposits in geological settings where rapid mineralization could have incorporated organisms into fine-grained, stable mineral phases. Examples of such environments include thermal-spring sinters (*e.g.*, Dao Vallis-Hadriaca Patera?), sublacustrine spring deposits (*e.g.*, Gusev Crater?), and evaporites/lacustrine shales (*e.g.*, White Rock?). Note that the cited examples have been derived from studies that are limited by the low resolution of most Viking data and a lack of mineralogical information. It is imperative that in the near term, site-selection activities focus on the identification of high-priority targets for high-resolution remote sensing, including visible imaging (for improved geological interpretations) and spectral data (for compositional mapping and mineral identification).

The search for extant life forms is equivalent to the search for liquid water which is likely to be present today only below the martian surface. During upcoming missions our best strategy for locating evidence of extant life is to search for cryopreserved organisms and biomolecules in ground ice that formed in association with recent outflows of subsurface water (*e.g.*, Ismenius Lacus), or water-rich pyroclastics (*e.g.*, lahars, Elysium?).

The refinement of priorities for future landed missions depends heavily on the success of upcoming orbital missions. High-resolution imaging will provide a basis for more accurate assessments of geological processes as well as relative age frameworks needed to evaluate the duration of hydrological systems for high-priority sites. Infrared and gamma-ray spectroscopic data are regarded as primary sources of information for targeting aqueous minerals and ground ice (respectively) and should be obtained prior to finalizing targets for future landed missions.

Finally, we need remote-sensing studies of analog environments on Earth using instruments similar to those to be flown to Mars. Such studies should simulate the spectral and spatial resolution of the orbital instruments to be flown in '96 and '98 to answer such basic questions as: What is the minimum spatial resolution required to detect key geological environments and deposits from orbit? What spectral regions within the IR are optimal, and what spatial resolution is required, for the detection of discrete aqueous mineral deposits from orbit? What is the optimal instrument design for detecting small thermal anomalies on Mars from orbit? Answers to such questions will be basic to the design of the next generation of instruments to be flown to Mars and to the analysis of Mars data once they are returned to Earth. Furthermore, they will be crucial in the continuing evolution and implementation of a strategy for the exobiological exploration of Mars.

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